Evaluating Evapotranspiration (ET) Landfill Cover Performance Using Hydrologic Models

Prepared for:
Air Force Center for Environmental Excellence
3300 Sidney Brooks
Brooks City-Base, TX 78235-5112

January 2004

Victor L. Hauser
Dianna M. Gimon

Mitretek Systems
13526 George Road
Suite 200
San Antonio, Texas 78230

Table of Contents

Figures

Tables

Appendices

1. Introduction

The technology available for landfill remediation is changing. New remediation methods are becoming available, and some are now being accepted by regulators. The old notion of entombment and preservation of waste is giving way to new concepts for managing wastes that may remove the threat to human health and the environment. Both old and new technology should meet the critical goal of landfill remediation, which is to protect human health and the environment.

Leading new technologies include (1) the landfill as a bioreactor (Reinhart and Townsend, 1998), and (2) the use of natural attenuation processes to enhance effectiveness of remediation at reduced cost by naturally renewable and continuing processes (ESTCP, 2002 and Downey and Hicks, 2003).

Although the regulatory community is actively investigating new technology, most enforcement personnel still prefer the *prescriptive remedies* and *preservation of waste* approach to landfill remediation. The currently accepted technology constrains the Air Force to continue with the concept of containment of the waste. However, a new landfill cover that satisfies the requirements of containment is rapidly gaining acceptance.

The new cover is called the evapotranspiration (ET) landfill cover. It is a complete cover, not a cover component. The ET landfill cover offers opportunities for improved performance and lower construction and maintenance cost. In addition, the new cover may be beneficial for use with bioreactor landfills because ET covers can be designed to pass a controlled amount of precipitation through the cover and into the waste.

Design, construction, and use of ET landfill covers is dependent upon the following:

- Definition of requirements for the cover
- Decision that an ET cover meets site cover requirements
- Selection of appropriate materials and ET cover construction methods that meet site-specific requirements

The ET landfill cover design problem includes complex relationships between climate, soil, and vegetation and is best solved with the aid of a computer model. ET landfill covers have different design requirements than do conventional covers; therefore, model requirements for design and evaluation differ from conventional practice. This report presents:

1. A discussion of cover requirements,
2. Design issues,
3. Currently available hydrologic models, and
4. An assessment of the accuracy and usefulness of engineering models that may be used to evaluate or design ET landfill covers.

2. Requirements and Definitions for Landfill Covers

Section 2 is an overview of requirements and definitions for landfill covers, and includes proof of the concept. Additional detail is available in Boyer et al., (1999), Gill et al., (1999), Hauser et al., (1999, 2001b, 2001c), Hauser and Gimon (2001), and Weand et al., (1999).

2.1. Landfill remediation requirements

The application of containment–the presumptive remedy–often requires the design and installation of a landfill cover. Other common components, such as landfill gas management, groundwater treatment or containment, and collection and disposal of leachate, may also be required. Landfill covers may offer several environmental benefits, but they are based on three primary goals:

1. Minimize infiltration of precipitation into the waste to control potential leaching of contaminants from the waste.
2. Isolate the wastes to prevent direct contact with potential receptors at the surface and to control movement of waste by wind or water.
3. Control landfill gases to minimize risks from toxic or explosive gases that may be generated within the landfill.

Because Air Force landfills are generally more than 25 years old (Hauser et al., 1999), they produce little gas, and many have produced minimal groundwater contamination. As a result, many Air Force landfills may not need gas or groundwater control. In addition, because of their advanced age and limited cover, many of them are already functioning as bioreactor landfills. Therefore, the landfill cover required for a site may have minimal requirements and may be the only remediation required.

2.2. Site-specific requirements for landfill covers

The site-specific requirements for landfill remediation should be developed before beginning design or selection of cover type. Site-specific requirements depend on numerous site-specific factors, including landfill history; waste type, quantity, and age; climate; geologic setting; local surface water and groundwater use; and regulatory requirements.

After a performance requirement has been established for remediating a particular landfill, any remedial alternative meeting that requirement can be selected and applied. Site-specific requirements are discussed in more detail in Weand et al., (1999) and in Boyer et al., (1999).

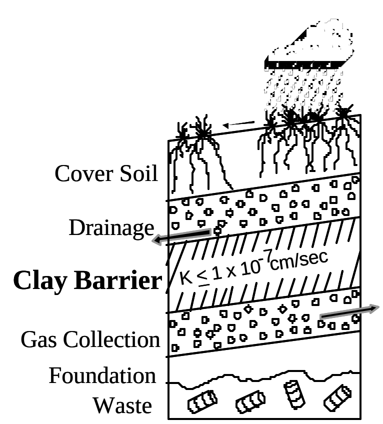

Figure 1 Conventional barrier-type cover

2.3. Conventional covers

The dominant feature of covers currently in use is one or more barrier layers that are intended to stop the natural downward movement of water through the profile of the cover. Conventional and barrier-type covers (Figure 1) include several layers, including grass for surface cover. These covers typically include one or more barrier layers made of compacted clay, geomembranes, or geosynthetic clay. Barrier-type covers are more completely described in Weand et al., (1999), Gill et al., (1999), Koerner and Daniel (1997), and U.S. EPA (1991, 1993, and 1996). The Subtitle D cover is a simplified barrier-type cover with a single barrier layer of compacted clay. It is less expensive than other barrier-type covers and is used in dry climates (Ankeny et al., 1997, and Warren et al., 1997).

Although barrier layers are sometimes referred to as *impermeable*, in practice this is seldom true. Suter et al., (1993) reviewed failure mechanisms for compacted soil covers in landfills; they concluded, "Natural physical and biological processes can be expected to cause [clay] barriers to fail in the long term." Melchior (1997) reported results of a German study in a cool, wet climate; he found that clay barriers were already leaking 150 to 200 mm per year in the eighth year of operation. Geomembrane barriers are also prone to leak. Board and Laine (1995) and Crozier and Walker (1995) traced most leaks in geomembranes to holes left by construction. Melchior (1997) reported that three composite covers, containing more than one barrier, leaked, on average, between 1 and 4 mm per year with annual leakage as high as 5.2 mm per year. Albright and Benson (2002) reported that conventional clay-barrier covers at two sites leaked 5.5 and 37 percent of the precipitation into the waste.

2.4. ET cover definition

Because of the water-holding properties of soils and the fact that most precipitation returns to the atmosphere via ET, it is possible to devise a landfill cover to meet remediation requirements, and yet contain no barrier layer. The ET cover consists of a layer of soil covered by native grasses; it contains no barrier or "impermeable" layers. Figure 2 illustrates the concept. The ET cover uses two natural processes to control infiltration: (1) soil provides a water reservoir, and (2) natural evaporation from the soil plus plant transpiration (ET) empties the soil water reservoir (Hauser and Shaw, 1994a and 1994b, and Hauser et al., 1994, 1995, 1996, and 2001b). The ET cover is an inexpensive, practical, and easily maintained biological system that will remain effective during extended periods of time—perhaps centuries—at low cost.

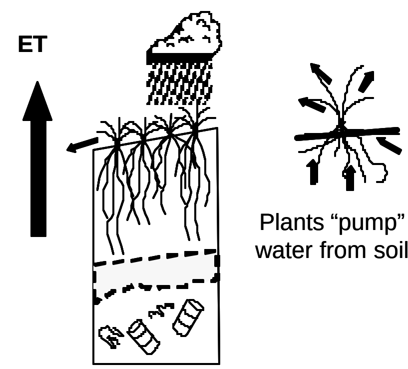

Figure 2 The ET Cover

The ET cover contains selected soil and requires correct placement to maintain desirable soil properties. Successful performance by the ET cover requires robust plant growth and good soil properties. It should be designed for the site to ensure that it meets the cover requirements.

2.5. ET cover concept verification

The technology that forms the basis for ET landfill covers was developed, tested, and well understood years ago, and field data are available from water balance measurements in both natural and constructed soil layers similar to those required for ET covers. The concept was corroborated in the field by both long- and short-term measurements that were collected during the past century (Figure 3). The long-term measurements established the water balance under grass during time periods from three decades to several centuries in length, and included unusually wet periods, fires, and other natural disasters. These data demonstrate that the ET cover can minimize movement of precipitation through soil covers by using natural forces and the soil's water holding capacity (Hauser et al., 2001b).

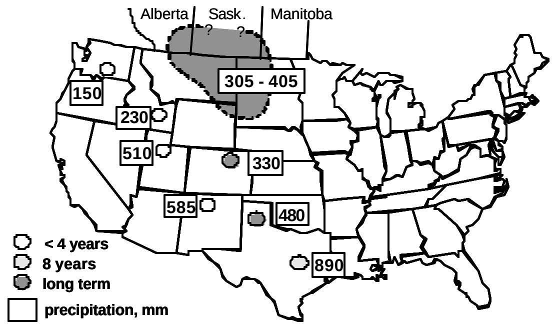

Figure 3 Field verification sites for ET landfill cover

2.6. Requirements for ET landfill covers

The ET cover has the following minimum criteria: (1) support a robust, healthy, vegetative cover, (2) the soil should allow rapid and prolific root growth in all parts of the soil cover, and (3) the soil should hold enough water to minimize water movement below the cover during extreme or critical design periods. In keeping with the requirements for all landfill remediation, the ET cover must meet the requirements for a landfill cover.

The soil and plants employed on the cover are critical to success. A mixture of grasses native to the area is preferred to provide effective water removal from the cover in all years in spite of temporary changes in local conditions. Native grasses have already proven their ability to withstand local climate variations, insects, plant disease, periodic fire, and other factors. A mixture of native grasses assures an active vegetative cover during years when insects, plant disease, or other factors reduce the vigor of one or more species (Hauser et al., 2001a & b).

The soil cover construction process is important because it has the power to assure success or cause poor performance of the cover. The ET cover uses a different mechanism to control water from that of conventional covers; therefore, the design and construction methods also differ. The soil of the cover should provide adequate plant nutrients, plant-available water holding capacity, aeration, soil strength, and other factors critical to rapid and robust plant growth, including the highly essential root system. Soil strength is particularly important because it limits the rate of plant root growth. Soil strength may be optimized by control of soil density during and after cover soil construction. These and other requirements are discussed in section 3.7, and by Hauser et al., (2001b and 2001c) and Weand et al., (1999).

3. Design Issues that Define Model Requirements

The ET cover cannot be tested at every landfill site, so it is necessary to extrapolate the results from sites of known performance to specific landfill sites. The factors that affect the hydrologic design of ET covers encompass several scientific disciplines and there are numerous interactions between factors. As a consequence, a comprehensive computer model is needed to evaluate the ET cover for a site. The model should effectively incorporate soil, plant, and climate variables, and include their interactions and the resultant affect on hydrology and water balance. An important function of the model is to simulate the variability of performance in response to climate variability and to evaluate cover response to extreme events. Because the expected life of the cover is decades, possibly centuries, the model should be capable of estimating long-term performance. In addition to a complete water balance, the model should be capable of estimating long-term plant biomass production, need for fertilizer, wind and water erosion, and possible loss of primary plant nutrients from the ecosystem.

Model needs are best met by an "engineering design model". In addition to requirements discussed here, an engineering model should require site parameters that can be measured or are available in historical records. Because adequate site-specific data are almost never available, the engineering design model should not require calibration

The properties of the ET cover and its design are different from those of conventional covers. Because model evaluation should include all of the important elements required in design, this section provides a review of important elements of the ET cover that influence its design and should be evaluated before selecting and using a particular model. The reader may find additional important detail in Appendices C through F, Boyer et al., (1999), Gill et al., (1999), Hauser et al., (1999, 2001b, 2001c), Hauser and Gimon (2001), and Weand et al., (1999).

Because borrow soils will be mixed and modified during placement, the cover soil for an ET landfill cover, as constructed, will be unique to the site. However, the soil properties may be easily described. The design process requires an evaluation of whether or not the proposed soil and plant system can achieve the goals for the cover. Numerous factors interact to influence ET cover performance. A mathematical model is needed for design that is capable of (1) evaluating the site water balance which is based on the interaction of soil, plant, and climate factors and (2) estimating performance of an ET landfill cover during extended future time periods.

Future predictions of ET cover performance require a sophisticated model. A suitable model should include the following:

- Contain a stochastic climate generator capable of simulating daily precipitation and other weather parameters that are similar in amount and statistical variability to historical weather records for the site
- Realistically estimate daily plant and soil response to variable generated climate
- Realistically estimate daily water balance including deep percolation

These requirements are similar to those required for flood flow estimates before designing a bridge or culvert on a roadway. In both cases, the future climate and resulting water balance are unknown, but an estimate of the critical future event and its probability of occurrence are needed to guide the design. These needs can be satisfied for ET landfill cover design or evaluation by a suitable hydrologic computer model.

This section describes elements that an engineering design model should simulate when designing an ET landfill cover.

3.1. Hydrologic water balance

A major requirement of a landfill cover is to control the amount of precipitation that enters the waste. The amount of water that percolates through the cover and may enter the waste is called deep percolation (PRK). Deep percolation is a part of a much bigger hydrologic system and must be assessed in parallel with the other parts. Therefore, it is necessary to estimate the entire hydrologic water balance for the cover in order to assess its behavior.

Because the quantity of water on or near the earth is believed to be constant, the hydrologic water balance for a landfill cover may be expressed by the statement:

"incoming water = outgoing water" or the following equation:

$$P + I = ET + Q + L + \Delta SW + PRK \qquad \textbf{Equation 1}$$

Where:
P = Precipitation
I = Irrigation, if applied
ET = Evapotranspiration (the actual amount, not potential amount)
Q = Surface runoff
L = Lateral flow
ΔSW = Change in soil water (SW) storage
PRK = Deep percolation (below cover or root zone)

An error in one parameter estimate produces an error in one or more of the others.

The site water balance for an ET landfill cover is illustrated in Figure 4. The incoming water (P+I) should equal the outgoing water (ET, Q, L, ΔSW, and PRK). Where all terms are measured, - e.g. lysimeter measurements - the difference or lack of balance is an expression of measurement error.

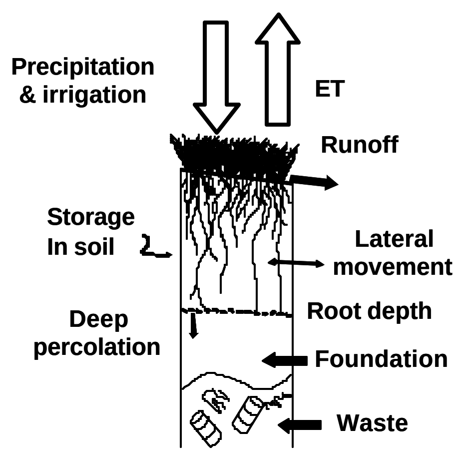

Figure 4 Water balance terms for an ET landfill cover

Lateral flow (L) within the soil layer containing plant roots is small for most landfill cover situations and is zero for lysimeters with sidewalls. During the course of a hydrologic year, ΔSW is usually small in comparison to the other terms, but it may be large on a daily basis. A primary focus for the design is deep percolation below the ET landfill cover as represented by the rearranged equation.

$$PRK = P + I - ET - Q - L - \Delta SW - error$$

error = lack of balance in the measured terms

PRK is the primary design criterion for landfill covers that are expected to limit and control the amount of precipitation that enters the waste of the landfill. As a result, the primary focus of model evaluation is the accuracy with which a model estimates PRK. However, the model estimate of PRK is strongly affected by errors in measured input P and I, and by errors in estimating ET, Q, and ΔSW. ET is the largest term of the outgoing water balance for almost all sites. Q is often the second-largest term; it is substantial at many, but not all, sites. Therefore, in addition to the accuracy of PRK estimates, it is also important to assess the accuracy of the model estimates of both ET and Q because errors in these estimates contribute directly to the error in PRK.

In a natural system, soil-water content changes in response to water removal by plants, soil evaporation, and gravitational drainage. During and immediately after rainfall or snowmelt, soil-water storage may change rapidly in response to the influx of water from the rain or snowmelt and the removal of water due to drainage by gravitational forces and plant use. While gravitational drainage can be a significant removal mechanism, it is effective for a short time and is near zero most of the time. Soil evaporation is important for one to a few days after precipitation; then it rapidly declines to near-zero amounts. Plant use is the primary mechanism for change in soil-water content and continues for long time periods or until the soil becomes dry.

Because soil-water content strongly affects daily values of ET, Q, and PRK, errors in estimates of change in total soil-water content will be included in errors of the ET, Q, and PRK terms estimated by a model. An appropriate model should continuously estimate the amount of soil-water in storage for all layers within the soil profile. The rate of plant water use and soil evaporation from a particular layer may be large or small depending on several interacting factors. A significant error in the amount of soil-water stored in one of the top soil layers may have no effect on the value of PRK if lower layers were dry on that day. Errors in estimates of soil-water storage in each individual layer may or may not contribute to errors in PRK, depending on water content of each layer of the entire soil profile and other factors.

The principles of water balance analysis are contained in numerous texts including Chow et al., (1988), Linsley et al., (1958), and Jensen et al., (1990). Water balance analysis for landfill covers is described in recent texts (Koerner and Daniel, 1997; McBean et al., 1995; American Society of Civil Engineers, 1996; Weand et al., 1999; and Gill et al., 1999).

3.2. Climate

Regional climate should be the first consideration when evaluating the suitability of an alternative landfill cover for a site. If the regional climate appears to be compatible with the requirements of the alternative cover, then site characteristics should be examined to determine whether the site climate is also suitable. Site and regional climate may differ substantially for sites near mountains, in valleys, in the rain shadow of coastal mountains, or near the coast. The Air Force Center for Environmental Excellence commissioned a generic assessment of the suitability of the ET landfill cover based on regional climate for the continental United States (Hauser and Gimon, 2001).

An adequate measurement of the climate at a site requires the longest available record and should contain a minimum of 20 years of data. The importance of long records can be illustrated by the annual precipitation from Coshocton, OH: while the 35-year average annual precipitation is 37 inches, one 5-year period averaged 88 percent of the overall average (32.6 inches) and another averaged 115 percent (42.6 inches). Clearly, a short record may not accurately describe the climate at a site and should not be used for design.

Site-specific climatic factors that are important to selection of landfill cover type and to design of ET landfill covers include daily measurements of precipitation, maximum and minimum temperature, relative humidity, total solar radiation, and wind run. If all of the data are not available, one can make useful—but less accurate—estimates of cover performance using only daily precipitation and maximum and minimum temperature measurements. Appendix C contains additional detail about climate.

Any model used for ET cover design should, at a minimum, be able to utilize daily precipitation and temperature data and preferably should be able to utilize the other important climate factors as well in order to produce the most accurate estimates.

3.3. Evapotranspiration

ET is the evaporation of water from the soil surface and by plant transpiration (primarily through the stomata on the plant's leaves). ET should be carefully considered during all stages of design since it will be the largest mechanism of water removal in the water balance for an ET cover. With current knowledge, it is necessary to estimate potential evapotranspiration (PET) first and then using the PET estimate the actual evapotranspiration (AET) for the site.

3.3.1. Potential evapotranspiration

PET is the maximum ET that can result from a set of climatic conditions. It is limited by the amount of energy available to evaporate water. The equivalent term "reference crop evaporation" is used by research workers who investigate the physics of evapotranspiration. For purposes of plant growth and production, PET is defined as the amount of water that would return to the atmosphere if abundant, freely transpiring plant leaves are available and the water supply to the plants is abundant and unrestricted. The magnitude of PET is useful for preliminary planning to identify the maximum possible performance that might be expected from an ET cover.

Hauser and Gimon (2001) estimated the ratio of PET to precipitation for the continental United States; the results are summarized in Figure 5. Hauser and Gimon (2001) arbitrarily used a PET ratio of 1.2 or greater to indicate likely success for the ET cover because actual ET is likely to be less than PET. The ratio of PET to precipitation is greater than one for almost all of the continental United States. The ET cover is likely to be appropriate for sites where the ratio is equal to or greater than 1.2; but it may also be appropriate and should be evaluated for all sites where the ratio is greater than one.

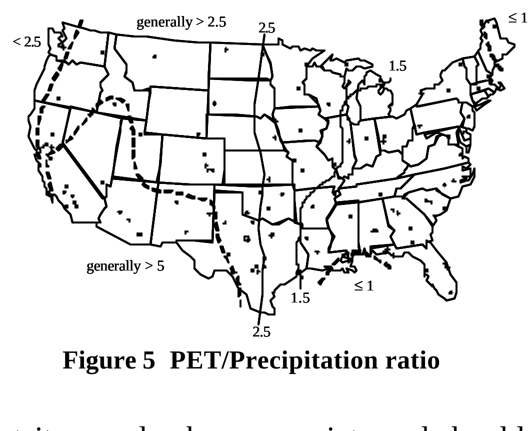

Figure 5 PET/Precipitation ratio

3.3.2. Actual evapotranspiration

AET is less than the PET amount except for relatively short time periods during and after rainfall or snowmelt events. When modeling performance of an ET landfill cover, the estimate of AET is very important. The accuracy with which a model estimates AET is the biggest controlling factor for hydrologic modeling accuracy because (1) AET is the largest term on the right-hand side of equation 1, and (2) water removed from the soil by AET affects or controls the size of the other terms on the right-hand side of equation 1.

Numerous factors control AET, and thus control the hydrologic performance of an ET cover. Soil-water content, rate of root growth, and total root mass strongly affect the rate of AET. AET is also affected by whether wet soil is available in surface soil layers, deeper in the profile, or in all layers. While root mass and root growth rate strongly affect AET, they are in turn controlled by other factors. Sections 3.5, 3.6, and 3.7 briefly discuss limitations on plant water use and provide references to additional information.

3.4. Surface runoff

Surface runoff (Q) is the second largest part of the hydrologic water balance for ET landfill covers at many sites in humid regions. Even at dry sites where surface runoff is small, errors in estimates of Q are important, and especially so if the model estimates significant Q on days with no runoff. Estimates of Q are therefore, important to the design process at all sites.

Water leaving the site as Q reduces the volume that must be stored within the cover. Errors in estimating daily Q will result in erroneous estimates of cover performance as measured by deep percolation of water below the cover. If the estimated Q is too low, the estimated PRK will be too high and vice versa.

Surface runoff can begin only after (1) rainfall or snowmelt fill storage by plant interception and surface ponding, and (2) the rainfall or snowmelt rate exceeds the soil infiltration rate. Excellent sources for technical details include Chow et al., (1988), Linsley et al., (1958) and ASCE Manual 28 (1996). Factors affecting Q are listed in Table 1.

Table 1 Factors affecting amount and rate of surface runoff.

Soil	Surface	Other factors
Infiltration rate	Surface crust and tilth	Rainfall intensity
Water content	Plant type (sod or bunch grass)	Timing of high intensity rain
Particle size distribution	Cover density	Storm duration
Frozen soil	Plant growth rate	Interception by plants
Bulk density	Stage of annual growth cycle	Soil surface depressions
Clay mineralogy	Biomass production	Litter on the soil surface
Macro porosity	Roughness and ponding	Land slope

Any model chosen for use in ET cover design should make reasonably accurate estimates of Q. There are several methods used to estimate Q. The ASCE Manual 28 (1996) discusses 18 engineering design models that compute Q; some of them use infiltration equations to estimate Q. One of the models used the Richards equation to estimate infiltration. One used the Smith & Parlange infiltration equation, and two used an “index”. Two models could use either the Soil Conservation Service (SCS) curve number method or the Green-Ampt infiltration equation. Nine of the models used the SCS curve number method and six used the Green-Ampt infiltration equation. The data shown in ASCE Manual 28 (1996) indicated that the SCS curve number method and the Green-Ampt infiltration equation are, by far, the most popular methods for estimating surface runoff in engineering design models. Additional detail regarding Q may be found in Appendix D.

3.5. Soil-water storage and movement

ET landfill covers control the precipitation falling on the surface by providing adequate water storage capacity in the soil to contain the infiltrating precipitation. Total (potential) soil-water storage capacity is controlled by soil properties. The storage capacity available at any instant in time is controlled primarily by the balance between infiltration from precipitation and rate of water removal from the soil by ET. The majority of ET is the result of plant transpiration. ET covers perform best when the primary limitation to plant growth is soil-water content, thus assuring rapid soil drying.

The physics of water movement within the soil is important to the design of an ET cover. The modern understanding of water movement in unsaturated soils has been under development for about 150 years, and the development of new concepts continues in the modern era. Henri Darcy (1856) provided the earliest known quantitative description of water flow in porous mediums. Darcy developed an equation for water flow in saturated sand, and modern equations for both saturated and unsaturated flow are based on his early work.

The currently used equations for water flow in unsaturated soil are based on the assumption that soils are similar to a bundle of capillary tubes and that water flow can be approximated by the Hagen-Poiseuille equation (Marshall et al., 1996). While it is obvious that the pore space in soil is not the same as a bundle of capillary tubes, the concept has proven highly useful and is currently used in mathematical descriptions of water flow in soil.

The Richards equation is widely used in research to estimate water flow in both saturated and unsaturated soils. It is also used in software proposed for use in evaluation of ET landfill covers.

For a more complete discussion of the Richards equation see Appendix E. Theoretical estimation of water flow in unsaturated soils is difficult and complex. The derivation of the versions of the Richards equation commonly solved in modern models required several assumptions. In addition, it is difficult to accurately estimate likely field values for unsaturated soil hydraulic conductivity on the scale of a complete ET cover. Nevertheless, the Richards equation provides useful estimates of flow of water within the soil where adequate estimates of soil hydraulic conductivity are available.

Other models successfully employ a simple water routing system. Each layer of soil is assumed to hold all water entering the layer up to the field capacity. When the water content of a soil layer exceeds the field capacity, water drains downward to the next layer at the rate specified by the hydraulic conductivity of the saturated soil in the layer.

Additional details regarding soil-water storage and movement that should be considered during design of an ET landfill cover are contained in Appendix E.

3.6. Deep percolation

Estimates of water movement through the cover (deep percolation or PRK) are of particular concern for ET cover design and evaluation. The performance of ET covers should be estimated for large and critical climatic events expected during the life of the cover. Therefore, a major concern for ET cover performance is the determination of the greatest amount of water that the ET cover soil must store during a defined time period. Critical events causing maximum soil-water storage may result from a single-day storm, a multiple-day storm, or other events.

The following example illustrates the concept. Model estimates are available for a landfill located on the western edge of the Central Great Plains; the cover soil was 0.6 m thick and composed of loam soil. Model estimates of soil water in storage for each day of a 100-year simulation period along with estimates of daily values of PRK are available. The estimates revealed that no water should be expected to move through the cover. Figure 6 presents the estimates of daily precipitation and daily soil-water content during the wettest year of the 100-year model estimate, and it includes the greatest single-day storage of soil-water during the 100-year period. In this example, the critical event was the result of several days with precipitation followed by a large, single-day precipitation event. The cover described could successfully control PRK.

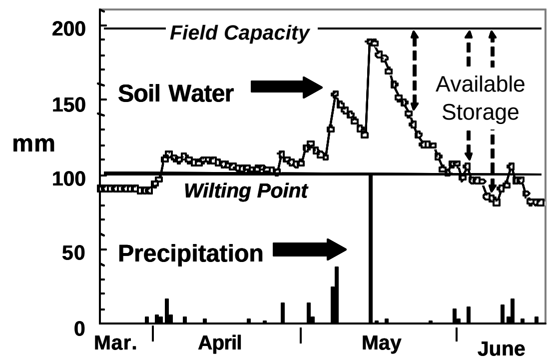

Figure 6 The critical event

Any model used for ET cover design should, at a bare minimum, demonstrate that the design being modeled will adequately control the projected critical event for the site being considered. Preferably, it should also estimate how much excess storage capacity would be available during that critical event so that an appropriate safety factor can be included in the final cover design.

Additional detail regarding factors that affect deep percolation may be found in Appendix E and in Hauser et al., (2001b and 2001c).

3.7. Soil

Soil provides the medium in which plants grow; it stores precipitation within the ET cover and provides nutrients for plant growth. Total (potential) soil-water storage capacity is controlled by soil properties. The storage capacity available at any instant in time is controlled primarily by the balance between infiltration from precipitation and rate of water removal from the soil by ET.

The cover design and construction should optimize soil conditions for water use by plants. This is an important tool and can be used to ensure success of the ET cover. Plant growth and water use are controlled by soil and air temperature, precipitation, solar radiation, wind, humidity, disease, and insect attack. Neither design nor construction practice can exert significant control over these factors; but they can be considered during design to assure success.

Other important soil properties of the ET landfill cover may be controlled by adequate design and good construction practice. These properties include:

- Density

- Aeration
- pH
- Nutrient status

After landfill cover completion, plant cover may be changed but soil modification may be impractical. Therefore, good soil design and correct construction practices are of utmost importance to the success of the ET cover.

The U.S. Department of Agriculture (USDA) soil classification system was developed for use in describing soils in which plants grow (SSSA, 1996, Hillel, 1980 and 1998, Gee and Or, 2002). The USDA system is now universally accepted within the United States and it should be used to describe soils used in ET landfill covers.

By its very nature, construction of an ET landfill cover modifies the soil used to create the cover. Hence, the construction process offers the opportunity to either (1) place the soil so that it will perform better than before it was moved or (2) damage the soil and greatly reduce the opportunity for success in meeting the requirements for the cover. It is important to understand soil properties that control success and how they may be optimized during cover construction. An appropriate model can help the designer understand how changes in the properties of soils available at the site in question will affect the final design of an ET cover.

Agricultural interests have amended existing soil properties to improve productivity; their experience demonstrates the power of knowledge of soil properties and the ability to control them (Taylor, 1967; Unger, 1979; Chichester and Hauser, 1991; and Hauser and Chichester, 1989). A primary benefit of these amendment efforts was improvement in soil-water holding capacity and increased rate of water removal from all soil layers by plants. The benefits of soil modification remain effective for decades (Unger, 1993; Musick et al., 1981; and Allen et al., 1995). There is opportunity for similar improvement in soil during ET landfill cover design and construction. Control of ET cover soil properties has potential to enhance cover performance and should add little to construction cost.

The water holding properties of ET cover soils are important to success. Soils that hold much water will achieve the desired water control with a thinner layer of soil than those with low water holding capacity. The water holding properties should be expressed as volumetric water content in keeping with model requirements and to facilitate understanding of design parameters. Important water holding properties include the permanent wilting point, field capacity, and plant-available water content.

Additional details regarding soil properties that should be considered during design of an ET landfill cover are discussed in Appendix E, Hauser et al., (2001b and 2001c), SSSA (1996), Hillel (1980 and 1998) and Carter (1993).

3.8. Plants

Understanding important plant requirements is critical for correct selection of materials, design, construction, maintenance, and performance of an ET landfill cover. The success of an ET cover is ensured by optimizing all factors controlling plant growth except for soil-water supply. The goal is to make soil-water content a limiting factor to plant growth several times during each normal growing season.

This section summarizes important plant issues that directly affect the performance of the ET cover and should be correctly modeled during cover design. Appendix E contains a discussion of plant and soil interaction, limitations on plant growth, and basic information about plant growth that is important to design.

The vegetation growing on the cover should be a mixture of grasses that are native to the site. Grass cover is preferred because it provides optimum erosion control and an extensive fibrous root system. However, where woody plants are appropriate, the design may be modified. Perennial species are preferred at most locations although annuals should be used where they are the predominant native species.

A mixture of native species will provide protection during periods when natural factors cause individual species to grow poorly. Because native species evolved at the site, they are known to be hardy and persistent. By definition, native plants survived for many centuries at the site under the existing climate. It is probable that they were subjected to extended drought periods longer than current historical drought, periodic fire and other adverse factors - yet they survived.

The plant cover should have potential rooting depth greater than the thickness of the soil cover. Many native species have potential rooting depths of two meters or more (Kiniry et al., 1995; Sharpley and Williams, 1990a).

Several plant parameters are important to the design of ET landfill covers. Among the most important are parameters describing: rooting depth, leaf-area-index, temperature requirements, time to maturity, and water requirements. Models that are suitable for use in design of ET covers will utilize these parameters. The quality of the plant model controls the quality of AET estimates. Appendix F contains a list of plant parameters that are important to the design of ET landfill covers.

3.9. Safety factor

As with any engineering design, the ET cover should be designed with safety factors because both design and construction introduce uncertainty regarding performance. Some safety factor concerns are similar between ET covers and conventional covers. However, control of water flow into the waste requires new safety factor considerations for the ET cover, including the following:

- The size of the soil-water reservoir in the cover soil should be adequate to contain extreme or design storm events
- The time required to empty the soil-water reservoir is critical to success

3.9.1. Soil thickness basis

One basis for providing a safety factor is to arbitrarily increase the soil thickness (e.g., build the soil 50 percent thicker than indicated as adequate by design). However, this intuitive approach may not produce the desired result.

Although the soil's total water-holding capacity is similar for all layers of a uniform soil, the distribution of roots and the rate and amount of water extraction are not. Consider the typical ET cover soil situation in which the soil has uniform properties from top to bottom. The distribution of living plant roots in soil controls the rate of drying of each soil layer. Figure 7 illustrates a normal root distribution pattern and an ET cover soil profile. Addition of extra soil to the thickness of the cover, where all soil is uniform, has the effect of adding soil to the bottom of the cover because the plant roots grow from the surface downward. The last increment of soil thickness results in relatively few roots growing in the newly added soil layer, which is effectively on the bottom of the cover. Plants remove water more slowly from deep soil layers than from near-surface soil layers. As a result, during one growing season, plant roots may not remove all plant-available water from the lower layers of the cover if the cover is thick.

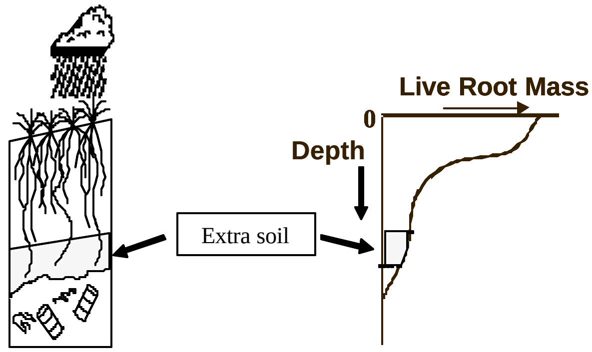

Figure 7 Root distribution in the cover

As shown in Figure 8, an increase in soil thickness from the design thickness (A) by 50 percent to (B) may result in only a small increase in plant available water holding capacity during a single growing season.

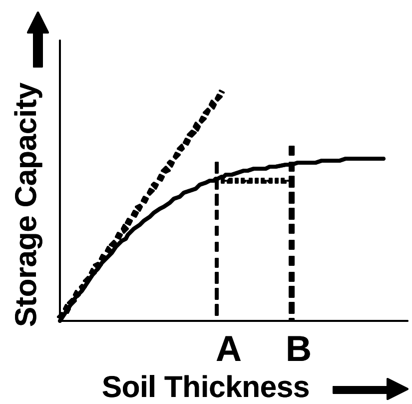

Figure 8 Effective water storage capacity - one growing season

3.9.2. Hydrologic basis

A better way to provide a safety factor is to utilize hydrologic factors that are known to affect soil-water use and storage. They may be used in combination with a model to evaluate options and select a good course of action. The model should estimate soil-water content for each soil layer on each day evaluated. It should also maintain a balance of available soil-water storage space. Therefore, the model should indicate available storage for each day along with ET, Q, and PRK. Possible ways to introduce an adequate safety factor include:

- Base the design on reduced plant available water holding capacity (e.g., 10% reduction)
- Base the design on increased daily precipitation (e.g., 110 percent of normal precipitation)
- Increase surface runoff by replacing the second layer of soil - e.g., 6 to 12 inches - with clay soil, or use a clay soil for the top six inches of the cover; but maintain the same soil thickness as required for a monolayer soil

- Design for either warm- or cool-season plants, but establish both to provide increased annual, total water use

These possibilities may be used singly or in combination.

Use of an appropriate model to simulate the effects of such design changes will enable the designer to add a suitable safety factor into the final design.

4. Hydrologic Models

ET landfill cover performance is governed by a complex set of interacting processes. Mathematical models may describe individual processes, but because of interactions among processes, these more limited mathematical treatments should be integrated into a single working model. The development of a new computer model suitable for ET landfill cover design would be expensive and require several years of development and testing. An alternative is to evaluate currently available models to determine whether they are suitable for design and analysis of an ET landfill cover.

Engineering design and cover evaluation are best served by a model that incorporates all of the important elements of engineering design that are important to ET covers. Some models are good research or scientific investigation tools, but are not sufficiently complete to serve the practicing design engineer who must consider all aspects of landfill remediation during cover design. In practice, the design engineer must balance the need for high quality, input data against landfill remediation requirements and available funds. The model should be sufficiently robust to provide reliable answers with less than optimum completeness or accuracy in the input data. It should also be capable of providing guidance to the design engineer regarding the consequences of incomplete input data.

This report section describes currently available models and presents important features of each that are pertinent to ET landfill cover design. These models have diverse origins; however, each was intended for use in evaluating the hydrologic cycle and included features that are pertinent to landfill covers. The model developer and/or other reviewers have tested each of these models. The purpose of this evaluation is to determine the level of accuracy and usefulness of a model as it might be applied to ET landfill cover design and evaluation.

4.1. Important model characteristics

If properly designed, the soil-water reservoir of an ET cover will be only partially filled most of the time. The greatest amount of water that must be stored in the soil will be defined by major or “critical events” (see Section 3.6). The critical event may result from a single storm event or a series of storms. The model used for design or evaluation of an ET landfill cover should be capable of evaluating the cumulative effect of each day’s water balance activity and thus identify critical events.

The design process requires estimates of the amount of water stored within the soil mass for each day of the design period. The performance of a completed cover or design may be assessed by estimating the daily, annual, or other sums of deep percolation, which can be used to determine whether or not the cover will meet design requirements.

Some models require calibration to optimize input parameters; they are best used in a research setting where it is possible to make measurements with which to calibrate the model for a particular site. Appropriate measured hydrologic data are seldom available to calibrate a model for a particular landfill site. Therefore, engineering models used for ET cover design should not require calibration.

The way in which models estimate potential and actual ET values, plant growth, root growth and distribution, and other parameters can have profound effects on the accuracy of model estimates for ET landfill cover design. For example:

- There are several possible methods for estimating potential ET (PET), the largest hydrologic term. Using the wrong method may introduce large errors in each part of the water balance analysis.
- The density of soil may control the presence, absence, or density of roots found in a particular soil layer (Eavis, 1972; Monteith and Banath, 1965; Taylor et al., 1966; Jones, 1983; Timlin et al., 1998; Gameda et al., 1985; Grossman et al., 1992; and Sharatt et al., 1998). The density of plant roots in a soil layer determines how much water plants can remove from the layer and its rate of removal. Soil compaction, in addition to inhibiting root growth, reduces soil-water holding capacity. A model that does not consider the effect of soil density on water balance may produce significant errors in water balance estimates.

4.2. Environmental policy integrated climate (EPIC) model

Development of the EPIC model and its predecessor, the Erosion Productivity Impact Calculator, began in the early 1980s [Williams, J. R. (personal communication, 1999), Mitchell et al., (1998), Sharpley and Williams (1990), and Williams et al., (1990)]. The first version of EPIC was intended to evaluate the effects of wind and water erosion on plant growth and food production. More recent versions also evaluate factors important to other environmental issues. EPIC is a one-dimensional model; however, it can estimate lateral flow in soil layers at depth. All versions of EPIC estimate surface runoff, PET, actual ET, soil-water storage, and deep percolation below the root zone — these complete the hydrologic water balance for an ET landfill cover.

More than 200 engineers and scientists participated in the development of EPIC and more than 50 publications describe testing and use of the model (Sharpley and Williams, 1990a). EPIC is in use by the Natural Resource and Conservation Service; the Agricultural Research Service of the USDA; Iowa State; Texas A&M; Washington State; the INRA of Toulouse, France; in Australia; Syria; Jordan; Canada; Germany; Taiwan; and other countries and universities around the world.

EPIC uses a daily time step to simulate climate, hydrology, soil temperature, nutrient cycling, tillage, plant management, and growth. It can estimate soil erosion, pesticide and nutrient movement by water or sediment, and field-scale costs and returns. The EPIC model has been revised and improved several times. From the beginning, the hydrologic sub-model was an essential and central part of EPIC because (1) the soil-water available for plant use is a limiting factor to plant growth, (2) surface runoff and soil erosion by water are directly related, and (3) deep percolation removes nutrients and other chemicals from the soil profile, which will affect plant growth.

EPIC is designed to simulate relevant biophysical processes simultaneously and realistically, using readily available input data and accepted methods. It is capable of simulating plant and soil response for hundreds of years, and it is applicable to a wide range of soils, climates, and plants. EPIC also simulates soil erosion and soil chemical and physical property changes over centuries. The time limit for simulation of hydrologic parameters is restricted only by the availability of quality climate input data.

EPIC contains ten major sub-models or components: (1) climate, (2) hydrology, (3) soil erosion by wind or water, (4) soil temperature, (5) tillage, (6) plant growth, (7) crop and soil management, (8) nutrient cycling, (9) pesticide fate, and (10) economics. Output from the soil erosion, pesticide fate, and economics sub-models may not be needed for ET landfill cover evaluation and design; they can be disregarded without affecting other components of the model estimate.

The EPIC model is a comprehensive model that has been extensively tested for water balance estimates in dry and wet climates, including sites with significant accumulation of snow in winter (Nicks et al., 1990; Cole and Lyles, 1990; Sharpley et al., 1990; Smith et al., 1990a; Smith et al., 1990b; Favis-Mortlock and Smith, 1990; Steiner et al., 1990; Cooley et al., 1990; Kiniry et al., 1990; and Sharpley and Williams, 1990b).

An important issue is the reliability of the model over the entire United States. EPIC was tested for accuracy in estimating ET and Q by many investigators on data gathered from the United States and other countries. Numerous tests of the model are described by Sharpley and Williams (1990a) and by others. Model tests by others are summarized below; in each of these evaluations, EPIC produced accurate estimates of ET and Q.

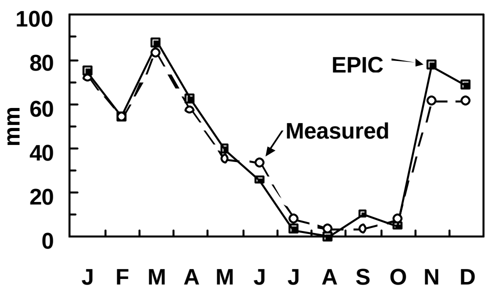

Figure 9 Average, monthly percolation during three years (Meisinger et al., 1991).

Estimates of water movement through the cover (deep percolation) are of particular concern for ET cover design and evaluation. Meisinger et al., (1991) demonstrated that EPIC estimated deep percolation with good accuracy when compared with measurements from high quality lysimeters at Coshocton, Ohio, Figure 9. Meisinger et al., (1991) state regarding the accuracy of EPIC "*The regression comparison of observed monthly percolation with predicted percolation for the 3-year period (36 data points) had an R^2 of 0.86, a slope of 0.86 (not statistically different from 1.0), and an intercept of 0.1 inches (not statistically different from zero).*" Chung et al., (1999) evaluated the performance of the EPIC model for two watersheds in southwestern Iowa and found that it estimated seepage flow well. Chung et al., (2001) evaluated EPIC against field measured drainage tile outflow in Minnesota and found that the model predicted annual drainage losses of similar magnitude to those measured, and replicated the effects of cropping systems on nitrogen fate in the environment.

In addition to a complete water balance, EPIC estimates plant biomass production, fertilizer use, wind and water erosion, loss of nitrogen and phosphorus from the soil, and the effect of nutrient loss from the soil on plant growth.

4.3. Hydrologic evaluation of landfill performance (HELP) model

The HELP model (Schroeder et al., 1994a and 1994b) is widely used and accepted for design of conventional, barrier-type landfill covers. The U.S. Army Engineer Waterways Experiment Station in Vicksburg, MS developed the HELP model for the U.S. EPA. Work began prior to 1982 as evidenced by the early publication of a draft report documenting hydrologic simulation modeling (Schroeder and Gibson, 1982). Recent versions of the HELP model are described in Schroeder et al., (1994a and 1994b).

Numerous workers tested the HELP model, and it is in general use throughout the United States by regulators, design engineers, and others for planning and evaluating barrier-type landfill covers.

The HELP model is a quasi-two-dimensional hydrologic model of water movement over, into, through, and out of landfills. It places primary emphasis on the properties and function of barrier and drainage layers located above and below the waste; such layers are typically used in barrier-type landfill covers. HELP uses climate, soil, and design data to estimate landfill hydrologic performance as expressed by surface storage, snowmelt, runoff, infiltration, ET, vegetative growth, soil moisture storage, lateral subsurface drainage, leachate recirculation, unsaturated vertical drainage, and leakage through soil, geomembrane, or composite liners. It is capable of modeling landfill systems that include various combinations of vegetation: cover soils, waste cells, lateral- drain layers, low-permeability barrier soils, and synthetic geomembrane layers for up to 100 years. The model was developed to estimate a water balance for landfills, cover systems, and solid waste disposal and containment facilities, emphasizing water percolation through the waste and performance of the landfill bottom liner. HELP provides estimates of surface runoff, ET, and drainage through the surface cover soil — these complete the hydrologic water balance for an ET landfill cover.

The primary purpose of the HELP model is to provide water balance data with which to compare design alternatives for conventional barrier-type covers installed on landfills with bottom liners. It provides a tool for both designers and permit-writers and is applicable to open, partially closed, or fully closed sites.

HELP does not address the effects of soil density on plant growth and the water balance. Although the HELP model was designed to evaluate barrier-type covers, it has not met expectations for the evaluation of vegetative covers. Benson and Pliska (1996) and Khire et al., (1997) evaluated the performance of the HELP model on two sites (Atlanta, Georgia and East Wenatchee, Washington). During a 3-year period, the HELP model predicted 4.4 times more PRK than was measured at Atlanta (a wet site) and half the measured amount in Washington (a dry site). At both sites, HELP produced large errors in estimates of PRK.

4.4. Unsaturated soil water and heat flow (UNSAT-H, version 3.0) model

Version 3.0 of UNSAT-H was developed under the sponsorship of the U. S. Department of Energy from the UNSAT model (Gupta et al., 1978) beginning in 1979. The early work was documented by publication of version 1.0 of UNSAT-H (Fayer et al., 1986), and the most recent version (3.0) was described by Fayer (2000). The UNSAT-H model has been tested for the arid parts of Washington State, a few other arid sites, and at least one location with a wet climate (Fayer, 2000).

Fayer (2000) states that the UNSAT-H model was developed to *"assess the water dynamics of arid sites and, in particular, estimate recharge fluxes for scenarios pertinent to waste disposal facilities."* It addresses soil-water infiltration, redistribution, evaporation, plant transpiration, deep drainage, and soil heat flow as one-dimensional processes. The UNSAT-H model simulates water flow using the Richards equation, water vapor diffusion using Fick's law and sensible heat flow using the Fourier equation.

UNSAT-H sets infiltration equal to the precipitation rate unless the surface soil becomes saturated. It does not simulate the soil crust that develops on the soil surface however, the user may describe a constant soil crust as a thin surface soil layer. It "*does not simulate runoff explicitly*" (Fayer, 2000); however, it assigns excess precipitation that does not infiltrate into the soil as surface runoff.

UNSAT-H uses the Richards equation, Fick's law, and the Fourier equation to estimate the flow of soil-water, vapor, and heat. This may be the strongest part of the model because these are the most rigorous, currently known, theoretical methods for estimating these parameters.

The UNSAT-H model estimates evaporation from the soil in two ways. In the isothermal mode, the user must supply PET data for each day or daily climate data from which the model calculates PET by the Penman method. In the thermal mode, the model estimates evaporation from the difference in vapor density in the atmosphere and in the surface soil layer.

UNSAT-H simulates plant transpiration with a PET concept. The model partitions plant removal of soil-water between soil layers based on (1) distribution of plant roots within the soil profile for "Cheatgrass" (an invading and weedy grass species found in dry regions of Washington State), or (2) the user may supply other functions. The user must enter soil-water parameters that describe the limits for plant extraction of water from each layer of soil. The model also uses the same daily value pattern for the leaf-area-index for each year.

The UNSAT-H model user must specify an averaging scheme for the internodal hydraulic and vapor conductivity terms used in soil water calculations. The user must also specify the model node spacing within the soil mass, which may require adjustment by iterative solutions to arrive at a satisfactory numerical analysis. In order to find the correct averaging scheme and node spacing, several "calibration" runs may be required to find systems that will work. These decisions are most appropriately made by a person with training in advanced soil physics and modeling.

UNSAT-H does not address the effects of soil density on plant growth and water balance. Disadvantages caused by the computational methods used to estimate soil water flow include: (1) the model requires the user to choose from several sub-models to solve the Richards equation; this choice should be made by a person with training in advanced soil physics, and (2) the model requires the input of several soil parameters which are difficult to estimate for the completed cover soil.

4.5. HYDRUS

The HYDRUS computer model was developed by the Agricultural Research Service of the U. S. Department of Agriculture to estimate water flow in unsaturated soils that support plant growth (Vogel et al., 1996). It was developed as a one-dimensional model, and then modified to allow solution of two-dimensional problems (IGWMC fact sheet). HYDRUS employs the Richards equation to solve water flow in unsaturated soil; however, it uses different solution methods from those used in UNSAT-H. It also requires extensive data input. The available windows version simplifies data entry and model operation.

4.6. Model comparisons

Table 2 compares characteristics of these four models. UNSAT-H and HYDRUS are the most widely known Richards equation models that use modern soil physics principles to estimate water movement within the soil profile. HELP and EPIC are widely known engineering models.

Table 2 Comparison of model characteristics.

Characteristic	EPIC	HELP	UNSAT-H	HYDRUS
Stochastic climate generator (daily values)	Y[1]	Y	N[1]	N
Daily water balance estimates				
Potential ET, (no. of options)	Y (4)	Y (1)	Y(1)	Y
Actual ET	Y	LAI[2]	Y	Y
Surface runoff, (no. of methods)	Y (2)	Y (1)	D[3]	D[3]
Deep percolation	Y	Y	Y	Y
Daily soil water balance	Y	Y	Y	Y
Snowmelt	Y	Y	N	N
Soil erosion by wind or water (no. of methods)	Y (4)	N	N	N
Soil density effect on root growth and water use	Y	N	N	N
Soil water flow	Routing[4]	Routing[4]	Richards[5]	Richards[5]
Uses potential plant rooting depth	Y	Y	Y	Y
Model estimates actual root growth	Y	N	N	N
Long-term estimates of plant nutrient availability and effect on water use by plants	Y	N	N	N
Mixed plant community	Y	UI[6]	N	N
Model calibration required?	N	N	**Y**[7]	Y[7]

1. Y = Yes, N = No
2. Based on leaf-area-index and "evaporative depth"
3. D = Difference between precipitation and infiltration rate (not directly estimated)
4. Water storage routing
5. Richards equation, vapor flow etc.
6. Requires independent user estimates for input data
7. Requires repeated runs to establish site-specific time step and grid mesh size which allow model convergence to a solution

4.6.1. HYDRUS and UNSAT-H

Examination of Table 2 and the comments above clearly demonstrate that both HYDRUS and UNSAT-H are likely to produce very good estimates of water movement within the soil profile. However, they do not estimate snowmelt, model mixed plant communities, directly estimate surface runoff, or consider the effect of soil density on root growth and water use.

Both of them require at least limited model calibration. They do not stochastically estimate daily climate data for model evaluations or long-term changes in plant nutrient status and the resulting changes in plant growth and water balance. HYDRUS and UNSAT-H would be very useful and accurate if used in research; however, they are difficult to use in engineering design of ET landfill covers and provide incomplete estimates of performance.

4.6.2. HELP and EPIC

Both HELP and EPIC satisfy the basic requirements for engineering design models, Table 2 and Sections 4.2 and 4.3. Limitations to HELP include difficulty in modeling mixed plant communities, and using the leaf-area-index (LAI) as the primary plant input to actual ET estimates. Both models are limited by their use of water storage routing to estimate water movement within the soil-water profile rather than modern soil physics principles. However, it is good to note that the water routing algorithms are based on modern concepts of soil physics.

Both HELP and EPIC are complete engineering design models and the user can obtain the data required to run either of them. The funds available were insufficient for evaluating more than two models on two data sets. Because our goal was to evaluate models that will be useful in ET landfill cover design and evaluation, we evaluated HELP and EPIC.

5. Methodology and Measured Water Balance Data

The purpose of this model evaluation effort is to determine if an existing model is adequate for design or evaluation of ET landfill covers and to identify its strengths and weaknesses. This purpose is different from one of model *validation*. Model validation includes detailed proof of mathematical functions, computer code representation of the real world, and similar issues.

We evaluated models which have previously been validated and tested, because the development of a new model suitable for the design task would be expensive and time consuming. This evaluation includes the following areas of concern for each model chosen:

- Accuracy of model estimates of evapotranspiration, surface runoff, and deep percolation
- Plant parameter inputs, their use within the model, and appropriateness for the design problem
- Soil parameter inputs, their use within the model and appropriateness of estimates that affect plant growth, and water use and storage
- Climate parameter inputs or generation
- Completeness of the hydrologic system evaluation
- Model output and satisfaction of design needs
- Level of support required from other models or other sources
- Model characteristics that may affect accuracy and completeness of ET cover design and/or evaluation

5.1. Selection of measured data for model evaluation

The accuracy and precision of the measured data are of paramount importance in model evaluation. Data sets from formal research projects in which measurements were recorded at hourly and/or daily intervals and also were monitored daily by investigators are most likely to meet this requirement.

Many variables should be measured to evaluate hydrologic response of a system, but inclusion of all variables greatly increases cost of the research. High quality research data are usually of short duration because of the cost for high quality long-term data sets. Therefore, one must seek data with good accuracy and precision and accept the longest available record.

In order to use existing data sets, one must often use data sets collected for a purpose other than model testing. In that case, the data should be assessed to determine if it is consistent with requirements stated in Sections 2, 3, and 4, and will meet the needs for model evaluation.

5.1.1. Requirements and sources for hydrologic data

The measured data used to evaluate models should come from a source that simulates the ET landfill cover as closely as possible. As explained in Sections 2, 3, and 4 above, the soil in an ET cover is a modified soil mixture and should be optimized for plant production during placement. As a result of mixing during construction, the soil in an ET cover may be more homogenous than native soils and thus be more simply described in a model than an undisturbed, natural soil profile.

The soils at many research sites and/or contained in lysimeters may be undisturbed and complex; they should be accurately described in order to assess model performance. Complexity of the soil is beneficial when it allows tests of important model functions that are required for ET cover design. The inclusion of bedrock or parent materials for the soil mantle within the experimental test soil may significantly increase the difficulty of model testing if the properties of these materials are incompletely described.

A valid premise of ET cover design is that waste will not impact the function of the cover because of the inherent need for good plant growth and limited interaction with materials under an ET cover. Therefore, any data that simulate an ET landfill cover may be suitable for model evaluation.

The test facility should account for all elements of the hydrologic water balance including precipitation, ET, runoff, soil-water storage, and deep percolation below the bottom of the soil profile. The data should be examined to determine the extent of error or bias resulting from insect attack, plant disease, hail, or high-density soil layers.

5.1.2. Weighing and recording lysimeters

Lysimeters are intended to accurately measure all water balance terms. The function of a weighing and recording research lysimeter is illustrated in Figure 10. Weighing and recording lysimeters are capable of measuring ET directly, in addition to precipitation, surface runoff, and deep percolation. Non-weighing lysimeters do not directly measure ET although they do provide an opportunity to measure other parts of the hydrologic water balance and often have associated instrumentation that allows an estimate of ET for the site. Daily change of soil-water storage may be estimated from weighing and recording lysimeter measurements, but it is often supplemented by direct measurements of soil-water content. Lysimeters are normally exposed to the prevailing climate at the site.

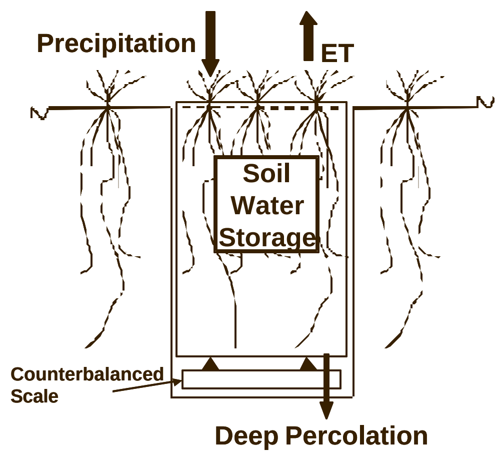

Figure 10 Weighing and recording lysimeter

Local advected energy may strongly affect the actual ET from a site near the edge between differing plant types or land uses; this phenomenon is called the “edge effect”. In order to assure representative estimates of ET with no “edge effect”, the lysimeter should be surrounded on all sides by a large area of plants similar to those in the lysimeter and having similar water supply.

5.2. Measured data sets used

High quality data were available from the Agricultural Research Service of the United States Department of Agriculture.

The data from the Coshocton, Ohio location were measured for the purpose of defining the hydrology of rural land in eastern Ohio. The data set that we used came from a lysimeter that was maintained to represent the same hydrologic condition during each year of the 17-year period.

The data from the Bushland, Texas location were collected to measure plant water use under irrigation on the Texas High Plains. The lysimeters use modern technology and they produce data of good accuracy and precision. However, the Bushland records were shorter than for the Coshocton data.

5.2.1. Bushland data set

Mitretek obtained measurements from two lysimeters located at the Conservation and Production Research Laboratory, USDA, Agricultural Research Service, Bushland, Texas. The lysimeters are located on the Texas High Plains, in a semiarid climate at the laboratory, 15 miles west of Amarillo, Texas at about 35.2^o N latitude, and 102^o W longitude. The elevation of the site is 1,170 m (3,840 feet) above sea level. The site is windy has low relative humidity and very high potential ET during summer. The Bushland site represents a dry to semi-arid condition where snow is a small part of the water balance, but winters are cold enough to kill or create dormancy for most plants during several months.

The measurements were for irrigated corn grown in one lysimeter during 1989 and 1990, and for irrigated alfalfa grown in another lysimeter during 1996 and 1997. Howell et al., (1989) described a corn experiment conducted at the site during 1987, and provided details regarding lysimeter operation and crop management. Lysimeter operations were similar for alfalfa to those described for corn, except that the alfalfa is a perennial crop and was not replanted during the test period.

The data were derived from measurements made with two large, weighing, monolithic lysimeters (Marek et al., 1988); they contain an undisturbed column of *Pullman clay loam* soil. Each lysimeter has a surface area of 9 m^2 and a soil depth of 2.3 m. They were installed in a 20-ha field with similar crops and irrigation treatment surrounding the lysimeter. The surrounding area with similar irrigated crops extended beyond the 20-ha field far enough to assure that there were no edge effects in the water balance terms measured by the lysimeters. The land at the site and over the adjacent fields has a surface slope less than one percent. The lysimeters were constructed with zero surface slopes and are capable of holding up to 76 mm (3 inches) of water on the surface; they allow no surface runoff. Additional detail about the lysimeters is contained in Marek et al., (1988).

Precipitation, irrigation, and ET were estimated from recorded lysimeter measurements. Precipitation and other climate measurements were available from a weather station operated at the site and also from station headquarters. Drainage outflows were small or zero, and were measured volumetrically. Soil-water content change was estimated from lysimeter measurements and from independent neutron meter measurements in the lysimeter soil. Research personnel worked at the site on five or more days of each week to assure high quality data. Personnel who collected and supplied the data are shown in the acknowledgements section of this report.

The soil at the site and in the lysimeter is the highly productive *Pullman clay loam* found on several million acres of the Southern High Plains of Texas, New Mexico, and Oklahoma (Unger and Pringle, 1981). It is productive under both dryland and irrigated crop production, and when used for grazing land.

An important feature of the Pullman soil is the high density layer from 0.45 to 1.8 m depth (Appendix G); the soil density is equal to or greater than 1.6. Tolk et al., (1997) reported data supporting the conclusion that the high density of the Pullman soil restricted root growth and thus water extraction. Tolk et al., (1998) reported that "Low grain yields from corn in the Pullman soil were due to limited water extraction from the lower soil profile."

Both sets of data from Bushland resulted from heavy irrigation in a semiarid climate. Because of the heavy irrigation there was opportunity for large amounts of PRK; however, only small amounts of PRK were measured. Appendix G contains a summary of available, measured input data, site descriptive information, monthly average climate data, and other statistics. Due to the length of the complete daily climate file, Appendix G provides only the first few lines as an example.

5.2.2. Coshocton data set

Mitretek obtained measurements from lysimeter Y101d located at the North Appalachian Experimental Watershed (NAEW), USDA, Agricultural Research Service, Coshocton, Ohio. The lysimeter is located in east central Ohio about 65 miles northeast of Columbus. The lysimeter and laboratory are about 10 miles northeast of Coshocton at 40.4^o N latitude and 81.48^o W longitude. The elevation of the lysimeter surface is about 361 m (1185 feet) above sea level.

The Coshocton site is cold and wet; snow produces a substantial part of the annual precipitation. The soil remains frozen and snow covered for several weeks during winter. The vegetation is similar to plant cover that might be established on an ET landfill cover in that region.

The measurements were made with a weighing and recording monolithic lysimeter (Figure 11) described by Harrold and Dreibelbis (1958), Harrold and Dreibelbis (1967), and by Malone et al., (1999). The dimensions of the soil block contained in the lysimeter is 4.267 m (14 feet) long, 1.896 m (6.22 feet) wide and 2.438 m (8 feet) deep, with the long dimension up and down hill. The surface area is 8.09 m^2 (0.002 acres).

The lysimeter soil block is an undisturbed natural soil profile from the site and includes bedrock in the bottom layers. The lysimeters were built deep enough to include bedrock so that drainage from the bottom would be natural. Thus, the lysimeters duplicated drainage conditions of the undisturbed, surrounding watershed.

The land slope around the lysimeter and on its surface is about 23 percent. Lysimeter Y101d is surrounded by similar vegetation for a distance greater than 305 m in all directions on government-owned land. The lysimeter and surrounding watershed were managed in "improved pasture or meadow." During the two periods for which measurements were evaluated, the plant cover was a 25/75 mix of alfalfa and orchardgrass or a 50/50 mixture of orchardgrass and bromegrass.

Precipitation and ET were estimated from recorded lysimeter measurements. Drainage from the bottom of the soil profile and surface runoff were independently and continuously measured volumetrically. Precipitation and other weather measurements were available from a weather station operated at the site and from station headquarters. Drainage outflow was substantial at this site. Soil-water content change was estimated from lysimeter measurements and from periodic and independent neutron meter measurements in the lysimeter soil. Measurements of hydrologic variables were automatically recorded; however, research personnel worked at the site on five or more days of each week to assure high quality data. Some of the personnel responsible for the experiment and those who supplied the data are shown in the acknowledgements section of this report.

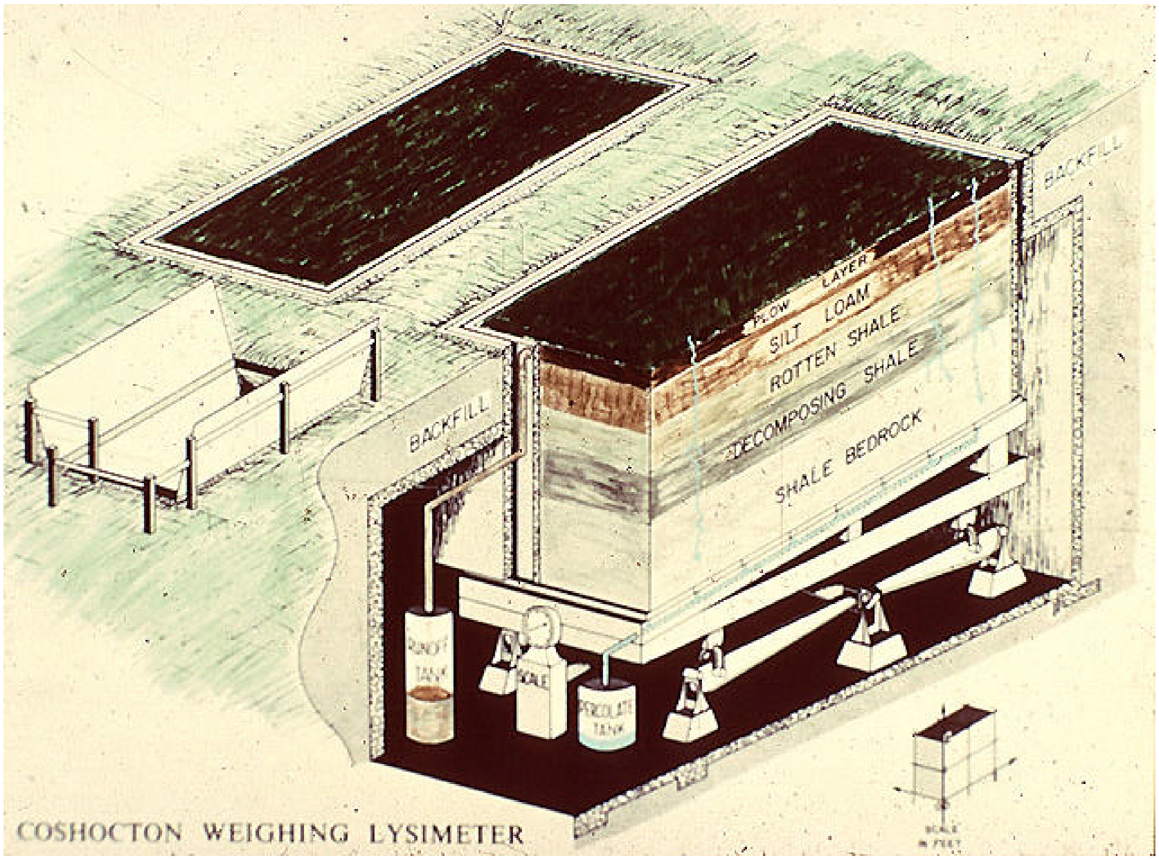

Figure 11 Weighing and recording lysimeter, Coshocton, Ohio, showing the undisturbed soil profile. Drawing courtesy Dr. James Bonta, North Appalachian Experimental Watershed, Agricultural Research Service, U.S. Dept. of Agriculture.

Complete measurements at lysimeter Y101d began on June 3, 1943 (Harrold et al., 1958). Mitretek obtained and used measured data for lysimeter Y101d including a total of 17 years of measurement during the years 1970-79 and 1987-93. This report describes the daily data used in model evaluation and statistics estimated for use by the models. Appendix H contains a summary of available, measured input data, and site descriptive information.

5.2.2.1. Soil and cultural measurements

The soils of the site were surveyed by Kelly et al., (1975); their survey focused on plant production factors. Harold and Dreibelbis, (1958), and Harrold and Dreibelbis, (1967), published hydrologic evaluation of the soils at the site. The soil description varied slightly between authors due to the focus of each study, natural variability at the site, and interpretation by individual observers. Appendix H contains the soil descriptions.

The plant cover and management varied between the two data sets; however in both cases, the plants and management were similar to the properties of those on an ET cover in the region. The investigators applied agricultural lime to the lysimeter to correct soil pH; this is not unusual for soils of the eastern United States. Due to removal of biomass during harvesting operations, loss by deep percolation, and other natural events, fertilizer was required to maintain a healthy and robust grass cover. Fertilization and lime applications varied in response to conditions at the site.

5.2.2.2. Climate data

NAEW recorded complete weather data at the site and at station headquarters located about 400 m (¼ mile) from the site. NAEW recorded precipitation data for the site in two data sets. The climatic data set contains precipitation data derived from a standard, class-A rain gauge at station headquarters. The Lysim101 data set contained daily precipitation measured by (1) a class-A rain gauge located near the lysimeter and (2) estimates of daily precipitation from the weighing and recording lysimeter records.

Daily climate input data were from the NAEW, station headquarters, Coshocton, Ohio, except as noted below. The data were recorded in English units and converted to metric units by Mitretek. Because the lysimeter measurements of precipitation were believed to be more accurate than the class-A gauge data, Mitretek used the daily, lysimeter measurements of precipitation for model evaluation (Appendix H). Appendix I contains a description of the data and steps taken to produce a useable set of data.

5.3. Lysimeter measurement errors

All field measurements proposed for use in model evaluation should first be evaluated for their accuracy because errors in the data limit the accuracy of the evaluation. The recorded data may contain random errors or cumulative, systematic errors; the type of error may be unknown.

The lysimeters at Coshocton and Bushland along with their associated infrastructure are among the best such facilities in the world. The accuracy of the data used in these evaluations may be assessed in at least two ways:

1. The precision of the lysimeters was previously estimated.
2. Because the data contain measurements of all parts of the hydrologic cycle, the mass balance, derived from the measured data, estimates error.

5.3.1. Lysimeter precision

Lysimeter Y101d at Coshocton, Ohio, was among the first modern field lysimeters to be built; it is still in operation. It is supported on a counterbalanced scale, and the overall accuracy of lysimeter Y101d is good. Harrold et al., (1958) reported that the precision of lysimeter Y101d was 0.25 mm of water equivalent (0.01 inch), by weight calibration. Malone et al., (2000) reported that the uncertainty of ET measurement was 0.36 mm/day (0.014 inch/day) before 1998 (the time period covered by these measurements). The precision of daily estimates of ET by the lysimeter is equal to or better than the accuracy of daily measurements of precipitation from good weather stations, and adequate to measure daily ET, or precipitation

Both lysimeters employed at Bushland, Texas, employ modern technology, thus they have good precision. Each lysimeter was supported on a counterbalanced scale. The precision of the measurement system is 0.045mm, equivalent water, which is adequate for hourly estimates of ET (Marek et al., 1988). The precision of these lysimeters is better than that of daily precipitation measurements at good weather stations.

5.3.2. Water balance errors

The weighing and recording lysimeters along with the associated instruments at both the Coshocton and the Bushland sites, provide measurements of each part of the hydrologic water balance, except for lateral flow. The lysimeter walls prevent lateral flow. Based on the principle of mass conservation, the water balance for a lysimeter may be derived from equation 2, Section 4, and expressed as:

Input to lysimeter = Output from lysimeter.

This relationship may be written as:

$$error = (P + I) - (ET + Q + PRK + \Delta SW)$$ **Equation 2**

Where:

P = Precipitation
I = Irrigation
ET = Evapotranspiration
Q = Surface runoff
PRK = Deep percolation below root zone or soil profile
ΔSW = Change in soil water content *(SW at end of time period – SW at beginning)*

Daily measurements of each term of the water balance equation, except for the error term, are available for each lysimeter. We calculated daily values of the error term and compiled monthly and annual summaries of the data. The size of the "error" term derived from the measured data provides an estimate of the error in the field measurements.

Because each lysimeter is automatically weighed and the data recorded at frequent intervals throughout the day, it is possible to use lysimeter measurements to estimate precipitation. Several authors describe errors associated with precipitation measurement at differing heights above the soil surface (Allis et al., 1963; Brakensiek et al., 1979; Chow, 1964; McGuinness, 1966; Neff, 1977; and Schwab et al., 1966). Their work leads to the conclusion that precipitation measurement by a precision lysimeter is more accurate than that from a standard rain gauge.

The lysimeter at Coshocton caught about 10 percent more precipitation than a nearby class-A rain gauge (Table 3). The difference was less at Bushland. Snow provides a large fraction of annual precipitation at Coshocton, but a relatively small part at Bushland. The lysimeters should more accurately measure snowfall than the nearby, class-A rain gauge. Snow measurements probably account for much of the difference in measured amount of precipitation at Coshocton.

We evaluated the water balance for both rain gauge- and lysimeter-measured precipitation. Table 3 contains the results of the water balance for each set of field measured data.

The data in Table 3 suggest that the overall measurement error of the lysimeter systems is in the range of +/- 15 percent. The range of error for measurements using lysimeter estimated precipitation is only -3.5 to +0.8 percent. However, where class-A rain gauge data are used in the balance, the error ranges from -15 to +11 percent, Table 3. The difference between water balance for rain gauge data and lysimeter data is smaller for Bushland than for Coshocton. However, precipitation measured by the lysimeter produced smaller errors in the water balance than the rain gauge measurements at Bushland.

It is unknown if the errors expressed by the data in Table 3 result from additive errors, random errors, or from other causes. The data in Table 3 emphasize the value of measurements of all parts of the hydrologic cycle so that an assessment of data accuracy may be made before testing models against the data. The daily error of the lysimeter measurements is equal to or less than the precision of a single class-A rain gauge reading for lysimeter measured precipitation at Coshocton and for all data sets at Bushland. However, the daily error for Coshocton lysimeter data using the class-A rain gauge data are both larger than the single class-A rain gauge reading.

Precipitation measurements by a standard class-A rain gauge are generally considered the best available for design use. Because all measurements of precipitation contain error, it is well to examine the potential error of class-A rain gauge measurements. The class-A gauge collects rainfall in a tube with a much smaller diameter than that of the catchment funnel. The “standard measuring stick” is calibrated to directly measure rainfall in inches or mm. The measuring stick is inserted into the tube and the rainfall total is read from the wetted portion. The stick is calibrated to read to the nearest 0.01 inch or equivalent reading. Because the water quickly climbs up by capillary action on the stick, it is difficult or impossible to estimate the reading closer than 0.01 inch or 0.25 mm.

As stated above, class-A rain gauge data are normally the best data available for design. It is advisable, however, to understand the potential error which could carry forward into a design with any model. For purposes of model evaluation, we used the best available precipitation measurements (lysimeter measurements) to test model accuracy.

Table 3 Water balance errors for measurements by the lysimeters. Water balance error is defined as input – output.

Location	Total[1] Input	Total[1] Output	Total Error[1]		Annual Error	Daily Error
	mm[2]	mm	mm[3]	%[4]	mm	mm
Coshocton, Meadow						
70-79, meas. by rain gauge[5]	9949	11456	-1507	-15.1	-151	-0.41
70-79 meas. by lysimeter[5]	**11067**	**11456**	**-389**	**-3.5**	**-39**	**-0.11**
Coshocton, Meadow						
87-93, meas. by rain gauge	6487	7226	739	11.4	106	0.29
87-93, meas. by lysimeter	**7170**	**7226**	**56**	**0.8**	**8**	**0.02**
Bushland, Alfalfa (2 years)						
meas. by rain gauge	2875	3013	-138	-4.8	-69	-0.19
meas. by lysimeter	**2953**	**3013**	**-60**	**-2.0**	**-30**	**-0.08**
Bushland, Corn (2 seasons[6])						
meas. by rain gauge	1568	1662	-94	-6.0	-47	-0.19
meas. by lysimeter	**1664**	**1662**	**2**	**0.1**	**1**	**0.01**
Precision of a single class-A rain gauge reading	-----	-----	-----	-----	-----	*0.25*

1. Total for the period of record shown
2. Precipitation + irrigation, if applied
3. Total error for the period of record shown
   Error = input - output = P + I – (ET +PRK + Q + ΔSW)
4. Error as a percentage of (precipitation + irrigation)
5. Precipitation measured by rain gauge or lysimeter
6. Water balance error for May 1 to December 31, in each of two seasons.

5.4. Hydrologic model evaluation

Scientific models are sometimes "calibrated" by half of the available data and verified against the other half of the data. While there are sound reasons for performing "calibration" in a research effort, that approach is not possible in the normal use of a model to design or evaluate an ET cover. A design engineer will have no data with which to "calibrate" a model.

We evaluated the usefulness of the HELP and EPIC models for engineering design of landfill covers as described in Section 4.6.2. Both models are described in Sections 4.2 and 4.3. We used these models as published and entered the measured and available data for each site. We did not change the parameters used within the models. We evaluated output for the purpose of verifying correct use of available, site-specific data within each model, and to assure that we correctly described the plants, soil, and climate at each site.

The measurements used for evaluation were for meadow grown in lysimeter Y101d during the periods 1970-79 and 1987-93 at Coshocton, Ohio; and for two years of data from each of two lysimeters planted in corn and alfalfa under irrigation at Bushland, Texas.

Section 3 and Appendices C through F contain discussion and detail regarding the use of and requirements for model input and output data. The models themselves are described in Section 4. Section 5.2 describes the input data used for each site. Appendices G, H, and I contain additional detail about the evaluation data and process. This section describes model-specific issues important to each evaluation.

We utilized lysimeter and climate measurements for each day of each calendar year during the 17 years at Coshocton, Ohio, and for the "alfalfa" data set at Bushland, Texas. The "corn" data set from Bushland only included data from the time of planting through the end of each year. Table 4 describes the data sets used for the model evaluations.

Table 4 Description of data sets.

Lysimeter	Years	Notes
Coshocton, Y101d, meadow	1970 - 1979	10 years, complete except for solar radiation
Coshocton, Y101d, meadow	1987 – 1993	7 years, complete record
Bushland, Alfalfa, irrigated	1996 - 1997	2 years complete, establishment year in 1995
Bushland, Corn, irrigated	1989 – 1990	2 years, complete during corn growing season and fall. Model evaluations during May 1 – December 31 for each year

5.4.1. HELP model evaluation

We obtained HELP version 3.07, from the U.S. Army Corps of Engineers website http://www.wes.army.mil/el/elmodels/index.html and used that version for all evaluations of the model. The HELP model can evaluate the water balance of all parts of a conventional, barrier-type landfill cover, the waste, drainage layers, and the bottom liner.

In this application, we used nine sub-layers within layer type one (top layer) to simulate the soil of the lysimeter. We did not use the other layer types that are typically used by HELP to estimate hydrologic performance of complete landfills.

The estimates were based on measured, daily values of weather parameters for the sites except for one data set. The HELP model estimated the daily 1970-79 solar radiation data for Coshocton, Ohio, using statistics derived from site data, as explained in Section 5.2.2 and Appendix I. The HELP model estimated ET, surface runoff, soil-water storage, and deep percolation from the bottom of layer number nine of layer type one.

HELP uses the modified Penman equation for PET estimates, and the curve number method to estimate surface runoff. In addition to site-specific data, we used the default values suggested in the model database.

5.4.2. EPIC model evaluation

We obtained EPIC version 8120 (EPIC8120) from the Texas A&M University, Blackland Research Center, website ftp://brc.tamus.edu/pub/meinardu/epic/epic8120/ and used that version for all evaluations of the model. EPIC can evaluate all parts of the water balance for a vegetated landfill cover; however, it was not designed to evaluate the hydrology of complete landfills.

The estimates were based on measured, daily values of climate parameters for the sites except for one data set. EPIC estimated the daily 1970-79 solar radiation data for Coshocton, Ohio, using statistics derived from site data, as explained in Section 5.2.2 and Appendix I. EPIC utilized 10 soil layers to describe the soils of each site. Unused parts of EPIC, such as wind and water erosion, and costs, were turned off within the model. These unused calculations have no effect on water balance estimates produced by the model. The associated program “UTIL” provided access to the data sets specific to model operation and contains a description of each variable along with suggestions for default values.

EPIC contains four methods for estimating PET; we used the Penman-Monteith method. EPIC contains subroutines for two methods to estimate surface runoff; we chose the curve number method. In addition to site-specific data, we used default values suggested in the model database.

6. Model Performance

We executed the EPIC and HELP models using the soil and plant parameters and the daily measurements of climate data available for each site. The models estimated water balance parameters for each day of the measured period. In this section we evaluate model performance.

All parts of the water balance equation are important to the design or evaluation of ET landfill covers. Because the amount of water that may percolate through the cover and into the waste is a major design issue for landfill remediation, the emphasis in model evaluation should be placed on PRK. Actual ET and Q together are usually much larger than PRK (Figure 12). However, errors in estimates of ET and Q affect the accuracy of PRK estimates; indeed, they can cause large errors in PRK estimates. Therefore, even though the focus of this model performance evaluation is on accuracy of PRK estimates, the accuracy with which a model predicts both ET and Q may define its usefulness in ET landfill cover design and can not be ignored.

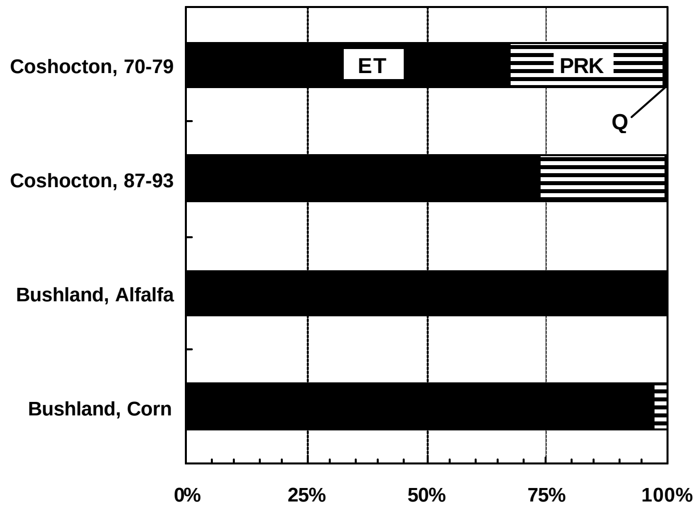

Figure 12 Fractions of the measured, outgoing water balance for Bushland and Coshocton.

An effective way to evaluate the model performance is to compare annual or monthly values estimated by the model with the similar measured events for ET, Q, and PRK. The value of total PRK for the month in which it reaches its maximum value during each year provides a surrogate for the critical event. Maximum monthly values of PRK for each year may also be used to measure model performance. The annual amounts and the maximum monthly value for each year lend themselves to statistical evaluation by classical methods. Therefore, it is possible to statistically assess model performance and thereby objectively assess model performance relative to another model or to hydrological measurements.

6.1. Internal hydrologic water balance of the models

Both the HELP and the EPIC models were previously tested before release by their developers. Each model was tested to assure that calculations within the model were accurate. Calculations within the model should satisfy the water balance expression contained in Equation 1 (Section 3.1).

We estimated the internal hydrologic balance of each model based upon the longest available record of measured water balance. Table 5 contains estimates of measured water balance errors and a comparison with model estimates for the Coshocton lysimeter Y101d, for the period1970-79. The walls of the lysimeter prevented lateral flow; (L) therefore, that term was zero in the water balance. The water balance error of the measured data was about 3.5 percent (Table 5); the error is similar to that from high quality hydrologic measurements.

The internal water balance for the EPIC model was -0.2 percent and for the HELP model it was near zero (Table 5). Internal model errors of this size are highly acceptable and expected for tested hydrologic models. However, the modeling errors for individual terms of the water balance are larger than the internal water balance error — as high as 20 percent of the measured precipitation.

Table 5 Water balance errors for the sum of lysimeter measurements and for the sum of model estimates for the 1970 through 79 time period at Coshocton, Ohio.

	Measured		**EPIC estimate**		**HELP estimate**	
	mm	Error		Error, %		Error, %
		%	mm	meas (prcp)[1]	mm	meas (prcp)[1]
Lysimeter precipitation (P)	**11,067**		11,067[2]		11,067[2]	
ET	**7,670**		7,532	-1.8 (-1.2)	5,472	-28.7 (-19.9)
Q	**63**		312	+395 (2.2)	669	+961 (5.5)
PRK	**3,678**		**3,173**	**-13.7 (-4.6)**	**4,917**	**+33.7 (11.2)**
ΔSW	**46**		32	-30.4 (-0.1)	10	-78.3 (-0.3)
L	**0.0**		----		----	
Sum (ET + PRK + Q + ΔSW)[3]	**11,457[4]**	**3.5**	11,049		11,068	
Model balance[5]				**-0.2[5]**		**<0.01[5]**

1. Errors as percent of measured variable or (lysimeter precipitation)
2. Measured, daily precipitation was input to model
3. Water balance equation: P = Sum(ET + PRK + Q + ΔSW) + error
4. Sum of measured values for water balance estimate
5. <u>Internal</u>, model hydrologic water balance

Even though both models had near-zero internal water balance error, they produced substantial error in individual terms of the water balance (Table 5). A small internal water balance error proves that calculations within the model are sufficiently accurate, but does not demonstrate the accuracy of the model for design activities. These models produced good internal water balances. The remainder of this section focuses on the question of how well the models may perform when used for design or evaluation of ET landfill covers.

6.2. Statistical evaluation of model estimates

The measured and estimated data for the Coshocton and Bushland sites were daily values of each parameter. The model estimates of annual ET, Q, and PRK, and extreme monthly PRK events are compatible with statistical evaluation. Therefore, the model evaluation includes statistical evaluation of the annual summations and the maximum monthly sum of PRK for each year. We determined which parameters were normally distributed before statistically evaluating model output.

Quantitative methods employing statistics may be used to evaluate model performance and provide a sound basis for model evaluation. Quantitative methods include both summary statistics and goodness-of-fit measures.

Summary statistics and goodness-of-fit measures were selected to evaluate model performance for both normally and non-normally distributed parameters following suggestions by Chung et al., (1999), Loague and Green (1991) and Zacharias et al., (1996). The normality of each parameter data set was assessed on the measured data using methods suggested by Gilbert (1987). These summary statistics and illustrations created from the data are the primary methods used to compare model output with the lysimeter measurements.

6.2.1. Summary statistics

Common summary statistics for the normally distributed values include the mean and standard deviation; they are defined in many text books. Because the mean and standard deviation should not be used to describe data that are not normally distributed, another means must be found to define model results and accuracy for those data. The median and median absolute deviation (MAD) are analogous terms and they may be used to describe non-normal data; however, they are less well known. The MAD is defined by Chung et al., (1999) and Zacharias et al., (1996) as:

$$MAD = 1.4826 \times median(|\, x_i - x_m \,| : i = 1,2...,n) \qquad \textbf{Equation 3}$$

where x_i is the *ith* observation, x_m is the sample median, and n is the sample size.

The differences between measured values and the model predicted values describe the usefulness of the model for both normally and non-normally distributed data. We described the difference as percent "error" which we define in equation 4:

$$error = \left[\frac{P_m - O_m}{reference} \right] \times 100 \qquad \textbf{Equation 4}$$

where P_m = predicted (model) mean or median, O_m = observed (measured) mean or median, and *reference* = reference value. The *reference* value is defined as the measured parameter value or measured lysimeter precipitation plus irrigation, as appropriate to the analysis. The reference value is stated for error estimates.

Percent error is an important measure of model performance; however, methods defined above for "error" may produce differing results. For example, from Table 5, the error of the PRK estimate by HELP is 1,239 mm during the 10-year period. The error based on the measured PRK value is 33.7 percent. The error based on total precipitation is only 11.2 percent. Even though the most obvious and intuitive assumption is that measured values should be used in estimating error; there are valid reasons for using total precipitation in error analyses as well.

Small parts of the hydrologic water balance, such as PRK are measured directly and independently in lysimeter measurements. Therefore, the measured value of PRK is accurate, precise, and independent of measurement errors for ET and Q. Model estimates of small hydrologic terms, such as PRK, contain increased error as a result of errors made by the model in estimating the larger terms; they are not independent from estimates of the large terms. Because terms such as PRK may be very small parts of the model-estimated water balance, their estimated error may be large when compared to the measured value.

It is important to define the error in a way that is consistent with the design goal and the intended use of the model estimates. A major concern in landfill cover design is the fraction of monthly or annual precipitation that may infiltrate through the cover and into the waste. Because the soil will store a significant fraction of monthly or annual precipitation, one may consider monthly or annual precipitation as the point of reference in making error estimates.

In this setting, the design engineer may seek to minimize the error of each term of the water balance equation relative to the most easily understood and available data – total precipitation. We used both measured values and precipitation as references for error estimates.

6.2.2. Goodness-of-fit estimates

Goodness-of-fit measures are based on an analysis of residual errors or differences between measured and model estimated parameters. They provide an estimate of the size of the difference between measured data and model estimates. The standard tests require that the data be normally distributed; however, there are alternatives for non-normal data.

We used goodness-of-fit estimates to further assess the accuracy of each model. The hydrologic variables were identified as normally distributed at the significance level of $\alpha = 0.1$ (10% level) as described by Gilbert (1987). Analysis of measurements revealed that the annual totals, and the maximum month totals for each year for ET and PRK, were normally distributed. The totals of Q measurements were not normally distributed.

Goodness-of-fit tests selected for evaluating the normally distributed estimates include (Chung et al., 1999; Zacharias et al., 1996; and Loague and Green, 1991):

1. RMSE = normalized root mean square error, %
2. EF = modeling efficiency
3. CRM = coefficient of residual mass

$$RMSE = \frac{100}{\overline{O}}\sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}}$$ **Equation 5**

$$EF = \frac{(\sum_{i=1}^{n}(O_i - \overline{O})^2 - \sum_{i=1}^{n}(P_i - O_i)^2)}{\sum_{i=1}^{n}(O_i - \overline{O})^2}$$ **Equation 6**

$$CRM = \frac{\left(\sum_{i=1}^{n}O_i - \sum_{i=1}^{n}P_i\right)}{\sum_{i=1}^{n}O_i}$$ **Equation 7**

where O_i and P_i are the observed (measured) and predicted values of each evaluation datum i, n is the number of observed and predicted value pairs, and $\overline{O}$ is the mean of the observed values.

The RMSE is a comparison between two data sets that is somewhat analogous to standard deviation of a single set of numbers. It is expressed as a percentage of the size of the variable. EF defines how well the model predicts the measured values and a value of 1.0 signifies perfect correspondence. CRM assesses the variance of model estimates from the measured data that is not explained by the model.

Goodness-of-fit tests selected to evaluate non-normally distributed estimates include (Chung et al., 1999; and Zacharias et al., 1996):

1. MdAE = normalized median absolute error, %, and
2. REF = robust modeling efficiency

$$MdAE = median\left(\left|O_i - P_i\right| : i = 1,2,...n\right) \times \left(\frac{100}{O_m}\right) \qquad \textbf{Equation 8}$$

$$REF = \left[\frac{\left(median\left(\left|O_i - O_m\right| : i = 1,2,...n\right) - median\left(\left|O_i - P_i\right| : i = 1,2,...,n\right)\right)}{median\left(\left|O_i - O_m\right| : i = 1,2,...n\right)}\right] \qquad \textbf{Equation 9}$$

where O_i and P_i are the observed (measured) and predicted values of each evaluation point i, n is the number of observed and predicted value pairs, and O_m is the median of the observed values.

MdAE and REF are functions suitable for use on non-normal data and intended to simulate the results of the RMSE and EF respectively.

We chose criteria for each summary statistic or goodness-of-fit statistic to aid the evaluation of model performance. These criteria are somewhat arbitrary; however, we chose the same criteria that were applied by Chung et al., (1999). These criteria provide uniform guidelines to indicate when estimates by a particular model deviate substantially from the measured data. They also provide a means to evaluate each model and to compare them with each other. Table 6 contains the criteria chosen to assess model performance.

Table 6 Criteria chosen to assess model performance for both normally and non-normally distributed variables.

Statistic for data with:	Optimum	Satisfactory results	Comment
Normal distribution			
Error (%)	0.0	-20< % error <20	+ = prediction high - = prediction low
RMSE (%)[1]	0.0	< 50%	
EF[2]	1.0	> 0.3	
CRM[3]	0.0	-0.2 < CRM < 0.2	- = prediction high + = prediction low
Non-normal distribution			
Error (%)	0.0	-20< % error <20	+ = prediction high - = prediction low
MdAE (%)[4]	0.0	< 50%	
REF[5]	1.0	> 0.3	

1. RMSE = normalized root mean square error, %
2. EF = modeling efficiency
3. CRM = coefficient of residual mass
4. MdAE = normalized median absolute error, %
5. REF = robust modeling efficiency

6.3. Performance – annual totals

Table 7 contains summary statistics for annual totals of daily values of ET, Q, and PRK. Because the parameters were normally distributed, annual means are compared for ET and PRK. Because the measured Q values were not normally distributed, model performance is more appropriately evaluated by median values of Q.

Table 7 Summary statistics for annual totals of ET, Q, and PRK. Percent error estimate based on measured parameter value. Boxed values exceed the criteria for satisfactory results (Table 6)

Average annual total													
	Measured				Model — ET			Model — Q			Model — PRK		
Data set/model	Prcp.[1] + Irrig.	ET[2] Mean	Q[3] Med.	PRK[2] Mean	Model[2] Mean	Error[4]		Model[3] Med.	Error[4]		Model[2] Mean	Error[4]	
	mm	mm	mm	mm	mm	mm	%	mm	mm	%	mm	mm	%
Coshocton													
70-79, EPIC	**11,067**	767	4.4	368	753	-14	-2	3.4	-1	$\boxed{-23}$	318	-50	-14
HELP	**11,067**	767	4.4	368	547	-220	$\boxed{-29}$	71.0	+67	$\boxed{+1,500}$	492	+124	$\boxed{+34}$
87-93, EPIC	**7,170**	764	1.2	276	732	-32	-4	0.0	-1.2	$\boxed{-100}$	259	-17	-6
HELP	**7,170**	764	1.2	276	570	-194	$\boxed{-25}$	7.2	+6	$\boxed{+500}$	429	+153	$\boxed{+55}$
Bushland													
Alfalfa EPIC	**2,953**	1514	0[5]	0	1460	-54	-4	0	0	0	0	0	0
HELP	**2,953**	1514	0	0	1478	-36	-2	0	0	0	71	+71	$\boxed{>1000}$
Corn, EPIC	**1,664**	809	0	22	867	+58	+7	0	0	0	31	+9	$\boxed{+41}$
HELP	**1,664**	809	0	22	869	+60	+7	0	0	0	5.5	-17	$\boxed{-77}$

1. Measured, mean annual precipitation + irrigation
2. Mean value
3. Median value
4. Error, mm or percent of measured parameter value
5. Bushland lysimeters prevented runoff, models predicted none

6.3.1. Annual total – ET error

The ET values displayed in Table 7 are measured and estimated values of AET. The estimates could contain errors derived from estimates of either PET or AET.

The HELP model uses the modified Penman method to estimate the PET at the site. The EPIC model contains four methods for estimating PET; we chose the Penman-Monteith method for the model estimates. Jensen et al., (1990) reported extensive tests of 20 different methods for estimating PET against data from many locations in many nations; they found that the Penman-Monteith method was the most accurate overall. Their analysis showed somewhat less dependable results with the Penman or the modified Penman methods. Therefore, the estimates of PET by EPIC may have been more accurate than those by the HELP model.

We did not assess the error in AET separately from PET because the measured data were for AET. The exact source of the difference in performance between the two models is therefore unknown. The most likely case is that both PET and AET estimates were in error for both models.

Inspection of Table 7 shows larger errors in both Q and PRK in association with large errors in ET estimates for the Coshocton data, thus emphasizing the importance of accurate estimates of ET. The errors in ET estimates were smaller for the Bushland data.

6.3.2. Annual total – Q and PRK error

Both models produced substantial errors for Q and PRK when evaluated against measured values of Q and PRK, Table 7. The probable cause is the size of the measured and estimated values relative to ET and precipitation.

It is important to note that using standard methods to describe the site conditions, both models estimated no runoff for the Bushland data where runoff was not allowed. It is important that models not predict runoff where none was produced; therefore, both satisfactorily estimated Q for the Bushland data. For the Coshocton lysimeters, both models produced Q estimates (Table 7) that are outside the limits set in Table 6. The EPIC model produced more accurate estimates than the HELP model (Table 7).

As explained previously in section 6.2.1, it is appropriate to examine model performance based on error estimates that use the precipitation value as the reference. Therefore, the annual totals for Q and PRK are evaluated using both the measured parameter and total precipitation values as reference for error estimates in Table 8.

Table 8 Summary statistics for annual totals of Q and PRK with percentage error based on both total precipitation and the measured parameter values as reference. Boxed values exceed the criteria for satisfactory results (Table 6).

Data set/model	Average annual total										
	Measured			Model — Q				Model — PRK			
	Prcp.[1] + Irrig.	Q[2] Med.	PRK[3] Mean	Model Med.[2]	Error			Model Mean[3]	Error		
						Prec.[4]	MP[5]			Prcp.[4]	MP[5]
	mm	mm	mm	mm	mm	%	%	mm	mm	%	%
Coshocton											
70-79, EPIC	**11,067**	4.4	368	3.4	-1	>-.1	$\boxed{-23}$	318	-50	-0.5	-14
HELP	**11,067**	4.4	368	71.0	+67	+0.6	$\boxed{+1,500}$	492	+124	+1.1	$\boxed{+34}$
87-93, EPIC	**7,170**	1.2	276	0.0	-1.2	>-.1	$\boxed{-100}$	259	-17	-0.2	-6
HELP	**7,170**	1.2	276	7.2	+6	+0.1	$\boxed{+500}$	429	+153	+2.1	$\boxed{+55}$
Bushland											
Alfalfa EPIC	**2,953**	0[6]	0	0[6]	0	0	0	0	0	0	0
HELP	**2,953**	0	0	0	0	0	0	71	+71	+2.4	$\boxed{>1000}$
Corn, EPIC	**1,664**	0	22	0	0	0	0	31	+9	+0.5	$\boxed{+41}$
HELP	**1,664**	0	22	0	0	0	0	5.5	-17	-1.0	$\boxed{-77}$

1. Measured, mean annual precipitation + irrigation
2. Median value
3. Mean value
4. Error, percent of measured precipitation
5. Error, percent of measured parameter value
6. Bushland lysimeters prevented runoff, models predicted none

The errors in both Q and PRK are less than 2.5 percent when estimated with measured precipitation as the reference (Table 8). The errors by the models are therefore consistent with the errors of high quality measurements of the hydrologic water balance. Error estimates based on the precipitation reference suggest that either model would be acceptable for engineering design of ET landfill covers. However, errors based on the measured parameter value reference, suggest that neither model is adequate for Q estimates and that the EPIC model is generally adequate for PRK estimates (Table 8).

6.4. Performance – surface runoff

There were large errors in the estimate for Q by both models (Tables 7 and 8). Additional insight into model estimates of Q may be gained from an examination of total runoff measured at Coshocton over the ten-year period from 1970-79. The HELP model (Table 5) predicted 10 times as much total runoff as was measured and EPIC predicted 5 times as much for the 10-year period.

Both EPIC and HELP use the SCS curve number (CN) method to estimate surface runoff; that method has been widely used in engineering design and evaluated by many investigators. The SCS CN method was developed from experimental measurements of storm runoff collected at sites east of the Rocky Mountains in the United States. It was developed, tested, and refined for estimates of storm runoff amount from small water sheds. The runoff estimates were intended for use in design of erosion control structures and ponds on farms and ranches.

Possible reasons for the substantial errors in surface runoff estimates for the Coshocton lysimeter Y101d include the following:

- The annual measured Q was a small part of the water balance; therefore, model estimates that were only a few mm in error, produced large percentage errors
- A large part of annual precipitation occurred as snow, but the CN method was developed primarily from rainfall runoff measurements
- The soil surface may have been more permeable when frozen than estimated by the models
- The SCS CN method was applied to all potential runoff events, both large and small, whereas the method was developed for the purpose of estimating large or extreme runoff events
- The standard CN (used in these estimates) may not represent the surface condition of the lysimeter
- The lysimeter surface was small in comparison to farm fields or watersheds for which the method was developed

More than one of these reasons may have influenced the model estimates of Q.

Figure 13 shows average measured monthly runoff amounts and estimates by EPIC and HELP for the Coshocton Y101d lysimeter during 1970-79. The models estimated more runoff than was measured during winter and early spring – the time when snowmelt normally dominates surface runoff. During the remainder of the year, both models estimated surface runoff with acceptable accuracy. The data in Figure 13 indicate that the most likely cause of the significant errors in surface runoff estimates shown in Table 5 was the accumulation and melting of snow. It appears likely that the soil was more permeable during the snowmelt season than predicted by the models. The data in Figure 13 suggest that the CN chosen for use in the models was appropriate during the eight warm months of the year when there were small amounts of measured Q, and model estimates were good.

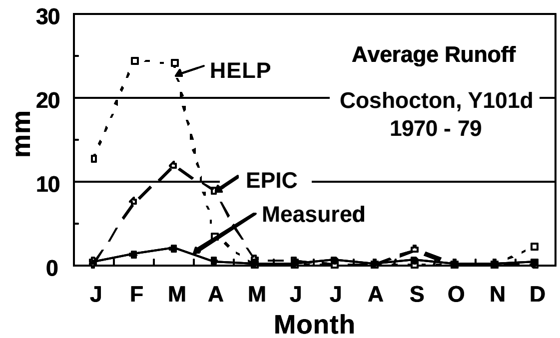

Figure 13 Ten-year average, monthly surface runoff, lysimeter Y101d.

6.5. Performance – annual maximum monthly PRK totals

Extreme values of PRK are important to the evaluation of ET landfill covers because they may define critical design requirements. The extreme values of PRK are a surrogate for the "critical event".

We selected the maximum monthly sum of PRK from each annual data set to test extreme value estimates. The maximum annual, monthly sum of PRK estimated by the model did not always occur in the same calendar month as the maximum measured monthly amount for a particular year. Therefore, the data sets indirectly assessed the month of occurrence as well as the monthly amount as variables in the comparison; both are important to evaluation of ET cover performance. Table 9 contains summary statistics for maximum monthly totals of PRK and estimates of the error produced by the models.

The significant errors in model estimates of surface runoff during winter at Coshocton (Section 6.4 and Figure 13 above) probably affected the model estimates of maximum monthly values and their timing. Thus, the Coshocton data tested the ability of each model to correctly estimate PRK for each month even though there were significant errors in other water balance terms during the year. This might be described as a test of the "robustness" of the models.

The hydrologic, water balance error for the measured data was 3.5 percent for the Coshocton measurements during 1970-79 (Table 5); that error was computed with precipitation as the reference value. The errors for PRK estimates by both models are less than 3.5% (Table 9) when estimated with precipitation as the reference. However, the errors in estimates of PRK with measured PRK as the reference are all larger than 3.5%. The estimates by the HELP model are greater than the criteria for acceptable performance on all of the data sets (Table 9).

Table 9 Summary statistics for mean values of annual maximum monthly totals of daily values of PRK. Boxed values exceed the criteria for satisfactory results (Table 6).

Data set/model	Prcp.[1] + Irrig.	Annual maximum monthly total PRK				
		Meas[2] Mean	Model[3] Mean	Error		
					Prcp.[4]	MP[5]
	mm	mm	mm	mm	%	%
Coshocton						
70-79, EPIC	**11,067**	102	122	20	0.2	19.6
HELP	**11,067**	102	205	103	0.9	101
87-93, EPIC	**7,170**	79	88	9	0.1	11.4
HELP	**7,170**	79	145	66	0.9	83.5
Bushland						
Alfalfa EPIC	**2,953**	0	0	0	0	0
Alfalfa HELP	**2,953**	0	47	47	1.6	>1000
Corn EPIC	**1,664**	22	24	2	0.1	9.1
Corn HELP	**1,664**	22	4	-18	-1.1	-81.8

1. Measured, mean precipitation + irrigation, mm
2. Measured mean, maximum monthly PRK, mm
3. Model estimate, mean, maximum monthly PRK, mm
4. Error, percent of measured precipitation
5. Error, percent of measured PRK

6.6. Statistical evaluation

The evaluation statistics described in Section 6.2.2 measure the goodness-of-fit of the model results to the measured data and provide additional insight into model performance. Tables 10, 11, and 12 contain a summary of the goodness-of-fit measures of model performance that were used in the statistical evaluation of model performance. The contents of these tables are based on the equations described in Section 6.2.2 and the performance criteria that are described in Table 6.

Table 10 contains the evaluation statistics based on annual totals of daily values. Table 11 describes the evaluation statistics based on annual, maximum month totals of daily values for PRK. Table 12 contains a summary of the statistical evaluation.

Table 10 Model evaluation statistics based on annual totals of daily values. Boxed values exceed the criteria for satisfactory results contained in Table 6.

Data set/model	ET			PRK			Q	
	RMSE[1]	EF[2]	CRM[3]	RMSE	EF	CRM	MdAE[4]	REF[5]
	%			%			%	
(Optimal value)	*(0.0)*	*(1.0)*	*(0.0)*	*(0.0)*	*(1.0)*	*(0.0)*	*(0.0)*	*(1.0)*
Coshocton, 1970-79, meadow								
EPIC	14.0	-6.8[7]	0.02	44.0	-0.19	0.14	123	-0.73
HELP	30.6	-36.2	0.29	45.7	-0.27	-0.34	1402	-18.7
Coshocton, 1987-93, meadow								
EPIC	9.4	-1.2	0.04	28.9	0.62	0.06	200	-1.29
HELP	26.8	-17.2	0.25	63.0	-0.83	-0.56	358	-3.10
Bushland, 1996-97, alfalfa								
EPIC	4.2	0.8	0.04	0*[6]	0*	0*	0*	0*
HELP	5.0	0.7	0.02	++[7]	++	++	0*	0*
Bushland, 1989-90, corn								
EPIC	7.3	-184	-0.07	56.2	0.68	-0.40	0*	0*
HELP	9.8	-329	-0.07	122.0	-0.49	0.75	0*	0*

1. RMSE = Normalized, root mean square error
2. EF = Modeling efficiency
3. CRM = Coefficient of residual mass
4. MdAE = Normalized, Median, Absolute error
5. REF = Robust modeling efficiency
6. * = No PRK or Q measured, model estimated none
7. ++ = No PRK measured, HELP predicted 71 mm/year (division by zero)

Table 11 Model evaluation statistics based on annual, maximum month, totals of daily values for PRK. Boxed values exceed the criteria for satisfactory results contained in Table 6.

Data set/model	PRK		
	RMSE[1]	EF[2]	CRM[3]
	%		
(Optimal value)	*(0.0)*	*(1.0)*	*(0.0)*
Coshocton, 1970-79, Meadow			
EPIC	29.9	-0.2	-0.19
HELP	110.0	-15.0	-1.00
Coshocton, 1987-93, Meadow			
EPIC	39.5	0.02	-0.12
HELP	91.5	-4.3	-0.85
Bushland, 1996-97, Alfalfa			
EPIC	0*[4]	0*	0*
HELP	++[5]	++	++
Bushland, 1989-90, Corn			
EPIC	11.9	0.99	-0.08
HELP	126.7	-0.6	0.83

1. RMSE = Normalized, root mean square error
2. EF = Modeling efficiency
3. CRM = Coefficient of residual mass
4. * = No PRK or Q measured, model estimated none
5. ++ = No PRK measured, HELP predicted 71 mm/year (division by zero)

Table 12 Summary of the statistical evaluation contained in tables 10 and 11.

Model	Satisfactory	Unsatisfactory
	Number	Number
	Annual totals	
EPIC	22	10
HELP	12	20
	Maximum monthly PRK	
EPIC	10	2
HELP	0	12

The normalized root mean square error for annual totals of ET were less than 15 for all model estimates except those by HELP for the Coshocton data (Table 10). The RMSE for HELP estimates from the Coshocton data were double and triple those for the EPIC model for the 1970-79 and 1987-93 data respectively (Table 10). The error measured in mm of water, of the ET estimate by the HELP model for the Coshocton data, was more than six times larger than for the EPIC model (Table 7) and did not meet the criteria for satisfactory performance.

The statistical estimates of performance by the models when estimating peak monthly values of PRK revealed clear differences in model performance (Table 11). The HELP model satisfied none of the requirements set for goodness-of-fit estimates of PRK (Table 11). The EPIC model met all of the requirements except for the EF statistic on the Coshocton data.

Table 12 summarizes the statistical evaluations contained in Tables 10 and 11. The data are the number of statistics that are either satisfactory or unsatisfactory for each model. The summary and Tables 10 and 11 show that the EPIC model performed better than HELP.

6.7. Performance – monthly estimates

Sections 6.1 through 6.6 focus on statistical evaluation of model performance. A more detailed examination of the data may reveal causes for the results discussed above and provide additional insight into model performance.

6.7.1. ET estimates

ET is the largest element of the estimated water balance parameters, and significant errors in estimates of actual ET reduce the accuracy of the estimate for other parts of the water balance. The data in Table 7 show that the error for HELP model estimates of ET exceeded the criteria for two of the four data sets.

Figure 14 compares the performance of the EPIC and HELP models as illustrated by average monthly values of ET measured by lysimeter Y101d at Coshocton, Ohio, for the longest available record of measured values. The EPIC model closely approximated all months except

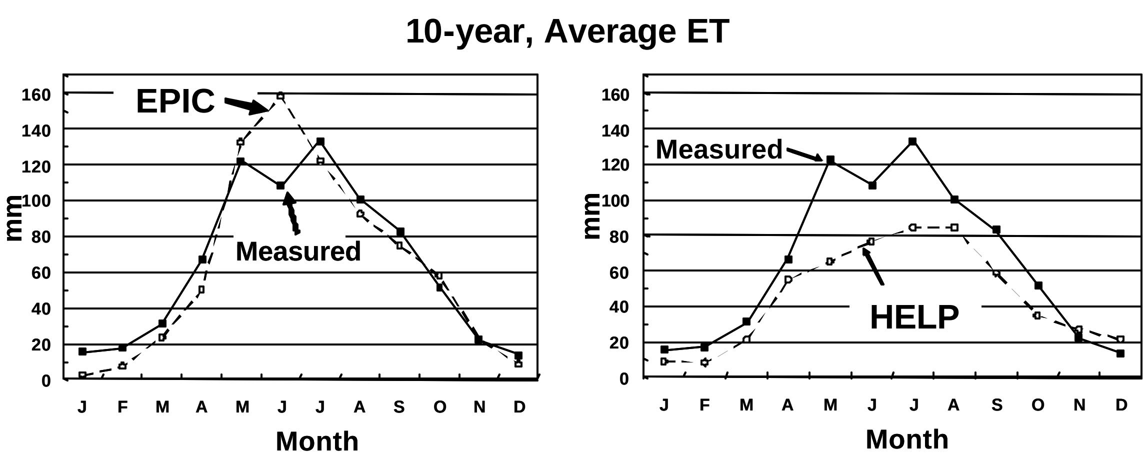

Figure 14 Measured and estimated average ET for lysimeter Y101d, at Coshocton, Ohio during 1970-79

June. However, the HELP model underestimated ET during May through September, which are the critical growing season months when maximum energy is available to evaporate water.

The apparently low value of measured ET during June is unexpected. In North America, potential ET for the month of June is higher than for any other month at most locations; as a result, actual ET is also normally at its maximum during June. The measured ET during June was also low for the 1987-93 record at Coshocton. June is a likely month for hay harvest from meadow, and although not found in the Coshocton records, may be the cause of reduced ET measured during June (Figure 14).

Figure 15 compares the performance of the EPIC and HELP models in estimating monthly values of ET measured by the lysimeters at Bushland for corn and alfalfa. The hot, dry climate

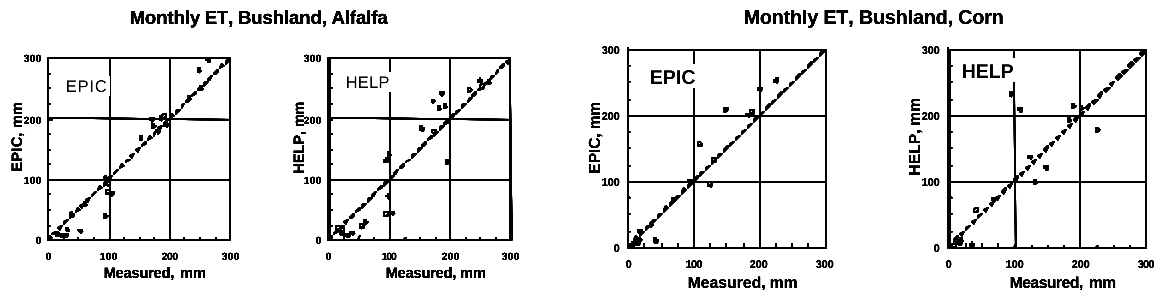

Figure 15 Comparison of measured ET with estimates by EPIC and HELP for corn and alfalfa at Bushland.

at Bushland during summer, results in very high ET rates. As a result, the requirements for ET estimation are different from those at Coshocton where the summer climate is humid, cooler, and less windy. The EPIC model estimated ET closely for each month for both corn and alfalfa at Bushland; however, the HELP model estimates were less consistent and overall they differed more from the measured values.

6.7.2. PRK estimates

The water balance parameter of greatest concern in evaluating ET landfill covers with models is the accuracy and reliability of PRK estimates. There was a substantial amount of PRK at Coshocton, but at Bushland there was none for alfalfa and a small amount in one year for corn. The EPIC model estimated PRK with good accuracy for both measured records at Bushland (Tables 7 and 8).

Because there was substantial PRK measured at Coshocton, we present a more detailed analysis for those data. Figure 16 compares the monthly values for PRK for each month of the 17-year record at Coshocton. In most of the months, PRK was small. EPIC estimated PRK values that were both too high and too low; however, the data cluster near the 1:1 line is expected for a reliable model. HELP, however, estimated several very large values when the corresponding measured value was small. The largest monthly amount of PRK estimated by HELP (280 mm) was for a month in which less than 50 mm of PRK was measured.

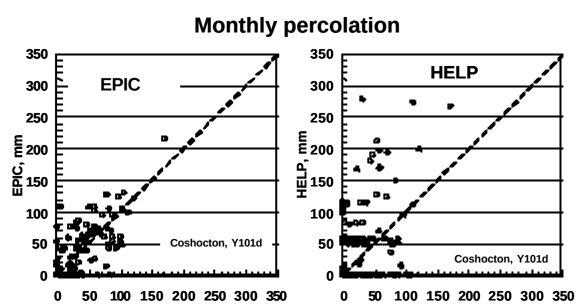

Figure 16 Comparison of measured monthly PRK with estimates by EPIC and HELP for the 17-year record at Coshocton.

Figure 17 shows measured and model estimated, monthly values of PRK for the 10-year period 1970-79 at Coshocton. A model should mimic the measured, natural pattern, as well as

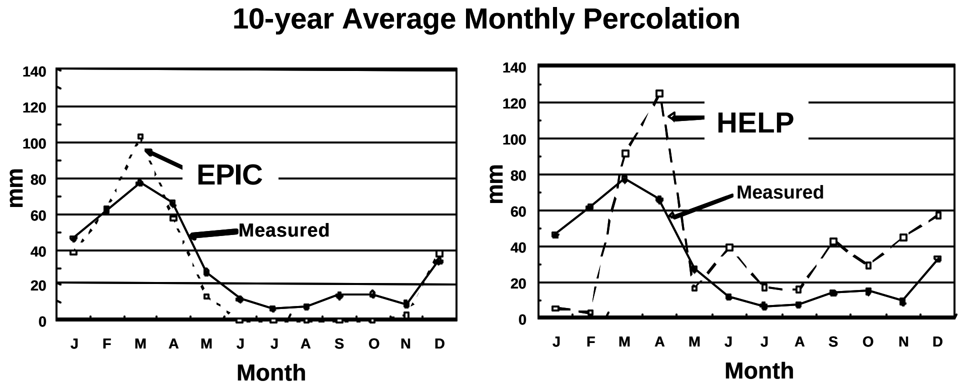

Figure 17 Comparison of average measured monthly PRK with estimates by EPIC and HELP for lysimeter Y101d at Coshocton during 1970-79.

the annual or monthly amount of PRK.

The estimate by EPIC for March was too high, but otherwise the estimates were acceptable and paralleled the measured amounts. The EPIC estimates were close to the measured amount for December, January, and February – all months with substantial snow and frozen soils. In addition, EPIC estimates of PRK followed the measured values during the growing season from April through November. The EPIC estimate for PRK in both February and April was near the measured value (Figure 17) even though there was error in the March estimate. This is evidence that the EPIC model is a robust engineering model that tends to return to correct estimates in spite of unknown factors that create errors in parts of the model estimates.

The HELP estimates were either too low or too high by substantial amounts (Figure 17); no pattern is obvious that explains the model performance. The HELP estimates of PRK during the growing season, April through November, were in substantial error (Figure 17).

7. Summary

This evaluation of the HELP and EPIC models utilized high quality data sets from two sites. The data sets available for this evaluation provide contrasts in hydrologic conditions, and therefore, they provide the opportunity for model comparison under widely differing conditions.

7.1. Accuracy of the models for use in design or evaluation of ET landfill covers

It is not enough to state that one model is better than another, because neither may be acceptable for use in design or for cover evaluation.

In order to evaluate whether a model is suitable, one should first attempt to understand the practical reality of site conditions. The climate data available to designers contains unknown errors and few, if any, are of the desired length. Descriptions of soil material and available information about plant response to climate and soils are imperfect. These limitations govern evaluation of ET landfill covers and limit the potential accuracy of model estimates.

The annual water balance errors found in the high quality lysimeter measurements used for these evaluations demonstrate the practical limits for model estimates of ET landfill cover performance. The range of the absolute value of the annual error for the rain gauge data varied between 47 and 151 mm (Table 3). The absolute value of total errors of the measured water balance using rain gauge precipitation measurements, are between 5 and 15 percent of average annual precipitation (Table 3). In the normal situation at a site, only rain gauge data are available for estimating site precipitation, thus a reasonable expectation for total error of annual model estimates may be assumed less than 10 percent of annual precipitation.

The errors in model estimates for ET were all less than 3.6 percent of the measured value based on annual precipitation (calculated from data in Table 7). The error in model estimates for PRK was less than 2.5 percent of the measured value based on annual precipitation (Table 8). These model evaluations demonstrate that using tested engineering models for design of ET landfill covers is a valid practice.

7.2. Relative performance of the models

Design and evaluation of ET landfill covers requires a focus on natural systems. The focus of the EPIC model is on the science and engineering involved in the interaction of climate, soil, and plants in natural systems and the resultant effect on hydrologic water balance. EPIC provides a relatively complete description of the natural processes that are important to performance of an ET landfill cover.

The HELP model was designed to evaluate the hydrology of complete, barrier-type landfill covers, including the cover, waste, bottom liner, and leachate collection. As explained in Section 4.3, the focus of the HELP model is on the manmade features of landfills and waste properties and not on natural systems that control the water balance of the cover. The HELP model achieves the goal set for it for manmade structures and waste but it is less accurate than desired for natural systems.

These evaluations clearly demonstrate that the EPIC model is adequate for ET cover design and evaluation and that it is significantly better than the HELP model. The HELP model has limited usefulness in design or evaluation of ET landfill covers. In all four comparisons evaluated in this study, EPIC produced substantially better estimates of ET, Q, and PRK than did HELP.

The extreme hydrologic event defines the maximum stress on the ET cover and determines whether a particular design is adequate for site requirements. Model estimates of maximum monthly PRK are of particular concern for ET landfill cover design and evaluation because the maximum monthly amount is a surrogate for the extreme event. The HELP model failed to meet the criteria established for maximum monthly PRK on any of the four lysimeter data sets. EPIC, however, exceeded the criteria set for all four data sets. In addition, the maximum error of the EPIC model estimates of maximum monthly PRK was 0.2 percent of annual precipitation (Table 9).

8. Acknowledgements

8.1. Bushland data set

Dr. Terry Howell, Research Leader for the Agricultural Research Service, USDA, at Bushland, Texas, provided data sets for corn and alfalfa grown in lysimeters – irrigated corn in 1989 and 1990 and irrigated alfalfa during 1996 and 1997 (personal communication, January 1999). Several research workers were involved in constructing the high quality lysimeters and in collecting the data set; they include Dr. Arland Schneider, Dr. Steve Evett, Karen Copeland, Don Dusek, Jim Cresap, Judy Tolk and Dr. Jean Steiner.

Address:
Conservation and Production Research Laboratory
P.O. Drawer 10
Bushland, TX 79012

Telephone: (806) 356-5734,
web page: http://www.cprl.ars.usda.gov/

8.2. Coshocton data set

Dr. James V. Bonta provided the first data sets and is currently located at Coshocton. Dr. Robert W. Malone supplied additional data and assisted with resolving problems encountered during data preparation for model testing; he is currently located at the USDA, ARS facility at Ames, Iowa. Dr's Bonta and Malone are the most recent engineers responsible for the long record of high quality measurements. Several other research engineers and scientists managed and collected results from the lysimeter, including L. L. Harrold engineer and F. R. Dreibelbis, soil scientist who were responsible for much of the important early work.

Address:
North Appalachian Experimental Watershed
P. O. Box 488
Coshocton, OH 43812

Telephone (740) 545-6349,
web page: http://www.ars-grin.gov/ars/MidWest/Coshocton/

8.3. Mitretek Systems staff

Mr. Mike Thomas created spread sheets to statistically determine whether data were normally distributed parameters.

Dr. Raymond S. Kutzman reviewed an early version of some sections of the document.

Dr. Barron L. Weand reviewed the draft document and provided valuable recommendations for change. He suggested improved presentations of results and the statistical analysis.

9. References

Albright, W. H and C. H. Benson. 2002. *Alternative Cover Assessment Program 2002 Annual Report*. Desert Research Institute, Reno, NV, Pub. No. 41182. Available at: http://www.dri.edu/Projects/EPA/acap.html#text

Allen, R. R., Musick, J. T. and Schneider, A. D. (1995). *"Residual deep plowing effects on irrigation intake for Pullman clay loam."* Soil Sci. Soc. Am. J. 59, 1424-1429.

Allis, J.A., B. Harris, and A.L. Sharp. 1963. *A Comparison of Performance of Five Rain-Gage Installations.* J. Geophysical Research 68, (no. 16): 4723-4729.

Ankeny, M.D., L.M. Coons, N. Majumdar, J. Kelsey, and M. Miller. 1997. *Performance and Cost Considerations for landfill Caps in Semi-Arid Climates.* In: Reynolds, T.D., and R.C. Morris (eds), Landfill Capping in the Semi-Arid West: Problems, Perspectives, and Solutions. Environmental Science and Research Foundation, Idaho Falls, ID.

ASCE Manual 28. 1996. *Hydrology Handbook 2nd Edition*. American Society of Civil Engineers, New York.

Benson, C. H. and R. J. Pliska. 1996. *Final Covers: HELP Needs Help From the Field.* Waste Age, vol. 27, no. 3, pp 89-98.

Board, M., and Laine, D. (1995). *Corralling liner nightmares*. MSW Management, 5(6), 48-51.

Boyer, I., V. Hauser, D. Gimon, and M. Gill. 1999. *Decision Tool for Landfill Remediation*. Air Force Center for Environmental Excellence, Brooks AFB, TX. Available at: http://www.afcee.brooks.af.mil/er/ert/landfill.htm

Brakensiek, D.L., H.B. Osborn, and W.J. Rawls (Coordinators). 1979. *Field Manual for Research in Agricultural Hydrology*. Agriculture Handbook No. 224. U.S. Department of Agriculture, Washington, D.C.

Carter, M. R., editor. 1993. *Soil sampling and methods of analysis*. Canadian Soc. of Soil Science, Lewis Publishers, Boca Raton, Florida.

Chichester, F. W. and Hauser, V. L. (1991). *"Change in chemical properties of constructed minesoils developing under forage grass management"*. Soil Sci. Soc. Am. J., 55(2), 451-459.

Chow, V.T. (Editor-in-Chief). 1964. *Handbook of Applied Hydrology*. McGraw-Hill Book Company, New York.

Chow, V.T., D. R. Maidment and L. W. Mays. 1988. *Applied Hydrology*. McGraw-Hill, New York, NY

Chung, S. W., Gassman, P. W., Kramer, L. A., Williams, J. R., and Gu, R. (1999). *Validation of EPIC for two watersheds in Southwest Iowa*. *J. Environ. Qual.* 28: 971-979.

Chung, S., P. W. Gassman, D. R. Huggins, and G. W. Randall. 2001. *EPIC tile flow and nitrate loss predictions for three Minnesota cropping systems*. J. Environmental Qual. 30: 822-830.

Cole, G. W. and Lyles, L. (1990). *The wind erosion component of EPIC*. *EPIC-Erosion/Productivity Impact Calculator, 1. Model Documentation,* U.S. Dept. of Agric., Agric. Tech. Bul. No. 1768.

Cooley, K. R., Robertson, D. C., Springer, E. P., Williams, J. R., and Hanson, C. L. (1990). *Evaluation of EPIC using a sagebrush range site*. *EPIC-Erosion/Productivity Impact Calculator, 1. Model Documentation,* U.S. Dept. of Agric., Agric. Tech. Bul. No. 1768.

Crozier, F., and Walker, T. (1995). *CQA + GLLS = TEC: How much does your liner leak?*. Wastes Management, 24-26.

Darcy, H. 1856. *Les fontaines publiques de la ville de Dijon*. Dalmont, Paris.

Downey, D. and J. Hicks. 2003. *Impact of Landfill Closure Designs on Long-Term Natural Attenuation of Chlorinated Hydrocarbons.* Proc. 2003 AFCEE Technology Transfer Workshop" 25 Feb. 03, San Antonio, Texas

Eavis, B. W. (1972). *Soil physical conditions affecting seedling root growth. I. Mechanical impedance, aeration and moisture availability as influenced by bulk density and moisture levels in a sandy loam soil*. Plant & Soil 36, 613-622.

ESTCP. 2002. *Impact of Landfill Closure Designs on Long-Term Natural Attenuation of Chlorinated Hydrocarbons*. Prepared by Parsons Engineering for Environmental Security Technology Certification Program, Arlington, VA, Final, March 2002. (available at: http://www.estcp.org/index.cfm)

Farahani, H. J., G. W. Buchleiter, L. R. Ahuja, G. A. Peterson and L. A. Sherrod. (1999). *Seasonal evaluation of the root zone water quality model in Colorado.* Agron. Jour. 91: 212-219.

Favis-Mortlock, D. T. and Smith, F. R. (1990). *A sensitivity analysis of EPIC*. *EPIC-Erosion/Productivity Impact Calculator, 1. Model Documentation,* U.S. Dept. of Agric., Agric. Tech. Bul. No. 1768.

Fayer, M. J., G. W. Gee and T. L. Jones. (1986). *UNSAT-H version 1.0: Unsaturated flow code documentation and application for the Hanford Site.* PNL-5899, Pacific Northwest National Laboratory, Richland, WA 99352.

Fayer, M. J. (2000). *UNSAT-H version 3.0: Unsaturated soil water and heat flow model - Theory, User Manual and Examples.* PNNL-13249, Pacific Northwest National Laboratory, Richland, WA 99352.

Flerchinger, G. N., R. M. Aiken, K. W. Rojas and L. R. Ahuja. (2000). *Development of the root zone water quality model (RZWQM) for over-winter conditions.* Trans. Of the ASAE 43: 59-68.

Gameda, S G., Raghaven, S. V. Theriault, R. and McKyes, E. (1985). *High axle load compaction and corn yield*. Trans. ASAE, 28(6), 1759-1765.

Gee, G. W., and D. Or. 2002. *Particle size analysis*. Section 2.4 in: Dane and Topp (editors), Methods of soil analysis, Part 4, Physical methods. Soil Science Society of America, Madison, WI.

Ghidey, F., E. E. Alberts and N. R. Kitchen. (1999). *Evaluation of the root zone water quality model using field-measured data from Missiouri MSEA.* Agron. Jour. 91: 183-192.

Gilbert, R. O. 1987. *Statistical methods for environmental pollution monitoring*. John Wiley & Sons, Inc., New York.

Gill, M.D., V.L. Hauser, J.D. Horin, B.L. Weand and D.J. Casagrande. 1999. *Landfill Remediation Project Manager's Handbook*. Air Force Center for Environmental Excellence, Brooks AFB, TX. Available at: http://www.afcee.brooks.af.mil/er/ert/landfill.htm.

Grossman, R. B, Benham, E. C., Harms, D. S., and Sinclair, H. R. Jr. (1992). *Physical root restriction prediction in a mine spoil reclamation protocol.* Proceedings of the 1992 National Symposium on Prime Farmland Reclamation, Dunker, R. E., Barnhisel, R. I. and Darmody, R. G. (eds.), Dept. of Agronomy, Univ. of IL, Urbana, 191-196.

Gupta, S. K., K. K. Tanji, D. R. Nielsen, J. W. Biggar, C. S. Simmons and J. L. MacIntyre. (1978). *Field Simulation of soil-water movement with crop water extraction.* Water Science and Engineering Paper No. 4013, Dept. of Land, Air, and Water Resources, Univ. of California, Davis.

Hanson, J. D., K. W. Rojas and M. J. Shaffer. (1999). *Calibrating the root zone water quality model.* Agron. Jour. 91: 171-177.

Harrold, L. L., and F. R. Dreibelbis. 1958. *Evaluation of agricultural hydrology by monolith lysimeters, 1944-55.* USDA, Tech. Bul. 1179, 166 pp.

Harrold, L. L. and F. R. Dreibelbvis. 1967. *Evaluation of agricultural hydrology by monolith lysimeters, 1956-62*.USDA, Tech. Bul. 1367, 123 pp.

Hauser, V. L. and Chichester, F. W. (1989). *"Water relationships of claypan and constructed soil profiles"*. Soil Sci. Soc. Am. J., 53(4), 1189-1196.

Hauser, V. L. and O. R. Jones. 1991. *Runoff Curve Numbers for the Southern High Plains.* Trans. ASAE, vol. 34, No. 1: 142-148.

Hauser, V. L. and M. A. Shaw. 1994a. *Water movement through soil-vegetative landfill covers.* ASAE paper no. 942176. Am. Soc. of Agric. Engineers, St. Joseph, MI 49085.

Hauser, V. L., and M. A. Shaw. 1994b. *Climate effects on water movement through soil vegetative landfill covers.* Seventeenth International Madison Waste Conference, Sept. Dept. of Engineering, Univ. of Wisconsin, Madison, WI.

Hauser, V. L., M. A. Shaw and B. L. Weand. 1994. *Effectiveness of soil-vegetative covers for waste sites.* Proceedings, Superfund XV, Washington, DC. Superfund XV, One Church Street, Rockville, MD 20850.

Hauser, V. L., M. A. Shaw, and B. L. Weand. 1995. *A natural cover for buried waste*. Proceedings, American Defense Preparedness Association, San Diego, CA

Hauser, V. L., B. L. Weand, M. A. Shaw and A. R. Wusterbarth. 1996. *Natural covers for landfills – a closer look.* Proceedings, American Defense Preparedness Association, 22nd Environmental Symposium, Orlando, FL.

Hauser, V. L., D. M. Gimon, D. E. Hadden, and B. L. Weand. 1999. *Survey of Air Force Landfills, Their Characteristics, and Remediation Strategies.* Air Force Center for Environmental Excellence (AFCEE), Brooks AFB, TX. Available at: http://www.afcee.brooks.af.mil/er/ert/landfill.htm

Hauser, V. L., and D. M. Gimon. 2001. *Vegetated Landfill Covers and Phytostabilization-The potential for Evapotranspiration-Based Remediation at Air Force Bases.* Air Force Center for Environmental Excellence (AFCEE), Brooks AFB, TX. Available at: http://www.afcee.brooks.af.mil/er/ert/landfill.htm

Hauser, V. L., M.D. Gill, D. M. Gimon, and J. D. Horin. 2001a. *Protocol for Controlling Contaminated Groundwater by Phytostabilization.* Air Force Center for Environmental Excellence (AFCEE), Brooks AFB, TX. Available at: http://www.afcee.brooks.af.mil/er/ert/landfill.htm

Hauser, V. L., B. L. Weand and M. D. Gill. 2001b. *Natural covers for landfills and buried waste.* J. Env. Engineering, vol. 127, No. 9:768-775

Hauser, V. L., B. L. Weand, and M. D. Gill. 2001c. *Alternative Landfill Covers*. Air Force Center for Environmental Excellence (AFCEE), Brooks AFB, TX. Available at: http://www.afcee.brooks.af.mil/er/ert/landfill.htmand from the Interstate Technology Regulatory Council at: http://www.itrcweb.org/common/default.asp

Hillel, D. 1980. *Applications of soil physics*. Academic Press, New York, NY.

Hillel, D. 1998. *Environmental soil physics*. Academic Press. San Diego, CA.

Howell, T. A., C. Copeland, A. D. Schneider, and D. A. Dusek. 1989. *Sprinkler irrigation management for corn – Southern Great Plains.* Trans. ASAE 32: 147-154.

IGWMC, *HYDRUS-2D for windows*. Fact sheet, International Ground Water Modeling Center, Colorado School of Mines, Golden, CO

Jaynes, D. B. and J. G. Miller. (1999). *Evaluation of the root zone water quality model using data from the Iowa MSEA.* Agron. Jour. 91: 192-200.

Jensen, M. E., R. D. Burman and R. G. Allen (editors). 1990. *Evapotranspiration and Irrigation Water Requirements*. ASCE Manual no. 70, American Soc. of Civil Engineers, New York.

Jones, C. A. (1983). *Effect of soil texture on critical bulk densities for root growth.* Soil Sci. Soc. Am. J. 47, 1208-1211.

Kelly, G. E., W. M. Edwards, L. L. Harold and J. L. McGuinness. 1975. *Soils of the North Appalachiean Experimental Watershed*. USDA, Washington, D. C., Misc. Pub. 1296

Khire, M. V., C. H. Benson, and P. J. Bosscher. 1997. *Water Balance Modeling of Earthen Final Covers.* J. Geotechnical and Geoenvironmental Engr., vol. 123, no. 8, pp 744 - 754.

Kiniry, J. R., Major, D. J., Izaurralde, R. C., Williams, J. R., Gassman, P. W., Morrison, M., Bergentine, R., and Zenter, R. P. (1995). *EPIC model parameters for cereal, oilseed, and forage crops in the northern Great Plains region*. Canadian J. of Plant Science, 75, 679-688.

Kiniry, J. R., Spanel, D. A., Williams, J. R., and Jones, C. A. (1990). *Demonstration and validation of crop grain yield simulation by EPIC*. *EPIC-Erosion/Productivity Impact Calculator, 1. Model Documentation*, U.S. Dept. of Agric., Agric. Tech. Bul. No. 1768.

Koerner, R.M., and D.E. Daniel. 1997. *Final Covers for Solid Waste Landfills and Abandoned Dumps.* American Society of Civil Engineers, Reston, Virginia. ASCE Press, 256 pp.

Landa, F. M., N. R. Fausey, S. E. Nokes, and J. D. Hanson. (1999). *Plant production model evaluation for the root zone water quality model (RZWQM 3.2) in Ohio.* Agron. Jour. 91: 220-227.

Linsley, R. K., M. A. Kohler, and J. L. H. Paulhus. 1982. *Hydrology for Engineers*. McGraw-Hill Book Co., New York.

Linsley, R. K., M. A. Kohler and J. L. H. Paulhus. 1958. *Hydrology for Engineers, Third Edition.* McGraw-Hill, New York, NY.

Loague, K, and R. E. Green. 1991. *Statistical and graphical methods for evaluating solute transport models: Overview and application.* J. Contaminant Hydrology, 7: 51-73. Elsevier Science Publishers B.V.

Malone, R. W., J. V. Bonta, D. J. Stewardson, and T. Nelsen. 2000. *Error analysis and quality improvement of the Coshocton weighing lysimeters.* Trans. ASAE, Vol. 43(2):271-280.

Malone, R. W., D. J. Stewardson, J. V. Bonta, and T. Nelson. 1999. *Calibration and quality control of the Coshocton weighing lysimeters.* Trans. Of the ASAE, 42(3);701-712.

Marek, T. H., A. D. Schneider, T. A. Howell and L. L. Ebeling. 1988. *Design and construction of large weighing monolithic lysimeters.* Trans. ASAE, 31: 477-484.

Marshall, T. J., J. W. Holmes and C. W. Rose. 1996. *Soil Physics*, 3rd edition Cambridge University Press, New York, NY.

Martin, D. L. and D. G. Watts. (1999). *Evaluation of the root zone water quality model for conditions in central Nebraska*. Agron. Jour. 91: 201-211.

McBean, E.A., F.A. Rovers, and G.J. Farquhar. 1995. *Solid Waste Landfill Engineering and Design*. Prentice Hall PTR, Englewood Cliffs, NJ.

McGuinness, J.L. 1966. *A Comparison of Lysimeter Catch and Rain Gage Catch.* ARS 41-124, Agricultural Research Service, U.S. Department of Agriculture. Washington, D.C.

Meisinger, J. J., Hargrove, W. L., Mikkelsen, R. L., Williams, J. R., and Benson, V. W. (1991). *Effects of cover crops on groundwater quality*. Cover Crops for Clean Water, Soil Conservation Society, 57-68.

Melchior, S. (1997). *In situ studies on the performance of landfill caps.* Proc. Intl. Containment Technology Conference, St. Petersburg, FL. 365-373.

Merva, G. E. 1995. *Physical principles of the plant biosystem*. Am. Soc. of Agricultural Engineers, St. Joseph, MI.

Mitchell, G., R. H. Griggs, V. Benson and J. Williams. 1998. *The EPIC Model, Environmental Policy Integrated Climate formerly Erosion Productivity Impact Calculator.* Manual, Texas Ag. Exp. Sta. and U.S. Dept. of Agric. Agricultural Research Service, 808 East Blackland Road, Temple, TX. 76502.

Monteith, N. H. and Banath, C. L. (1965). *The effect of soil strength on sugarcane growth.* Trop. Agric., 42, 293-296.

Musick, J. T., Dusek, D. A. and Schneider, A. D. (1981). *Deep tillage of irrigated Pullman clay loam, a long-term evaluation.* Trans. ASAE, 24(6), 1515-1519

Musick, J. T., O. R. Jones, B. A. Stewart and D. A. Dusek. 1994. *Water-yield relationships for irrigated and dryland wheat in the U.S. Southern Plains.* Agron. J., 86: 980-986.

NCDC. 2001. *Daily Climatic Records for the United States*, National Climatic Data Center, published by Earthinfo, Inc, Boulder, CO.

Neff, E.L. 1977. *How Much Rain Does a Rain Gage Gage?* J. Hydrology 35:213-220.

Nicks, A. D., Richardson, C. W., and Williams, J. R. (1990). *Evaluation of the EPIC model weather generator.* EPIC-Erosion/Productivity Impact Calculator, 1. Model Documentation, U.S. Dept. of Agric., Agric. Tech. Bul. No. 1768.

Othmer, H., B. Diekkruger, and M. Kutilek. 1991. *Bimodal porosity and unsaturated hydraulic conductivity.* Soil Science, vol. 152 (3): 139-150.

Philip, J. R. 1954. *An Infiltration Equation with Physical Significance*. Soil Sci. vol. 77: 153-154

Reinhart, D. R., and T. G. Townsend. 1998. *Landfill Bioreactor Design & Operation*. Lewis Publishers, Boca Raton, FL.

Rendig, V. V and H. M. Taylor. 1989. *Principles of soil-plant interrelationships*. McGraw-Hill, New York, NY.

Russell, R. S. 1977. *Plant root systems: their function and interaction with the soil*. McGraw-Hill Book Co., Ltd., London & New York.

Savabi, M. R. 2001. *Determining soil water characteristics for application of WEPP model in south Florida*. Trans. Of the ASAE, vol. 44 (1), 59-70.

SCS. 1972. *National Engineering Handbook: Section 4, Hydrology*. U. S. Department of Agriculture, Soil Conservation Service (now named: Natural Resource Conservation Service), Washington, DC.

Schroeder, P. R., T. S. Dozier, P. A. Zappi, B. M. McEnroe, J. W. Sjostrom, and R. L. Peyton. 1994a. *The Hydrologic Evaluation Of Landfill Performance (HELP) Model: User's Guide for Version 3.* EPA/600/R-94/168a, U.S. Environmental Protection Agency Risk Reduction Engineering Laboratory, Cincinnati, OH.

Schroeder, P. R., T. S. Dozier, P. A. Zappi, B. M. McEnroe, J. W. Sjostrom, and R. L. Peyton. 1994b. *The Hydrologic Evaluation Of Landfill Performance (HELP) Model: Engineering Documentation for Version 3.* EPA/600/R-94/168b, U.S. Environmental Protection Agency Risk Reduction Engineering Laboratory, Cincinnati, OH.

Schroeder, P.R. and A. C. Gibson. 1982. *Supporting documentation for the hydrologic simulation model for estimating percolation at solid waste disposal sites (HSSWDS).* Draft Report, US Environmental Protection Agency, Cincinnati, OH. 153 pp.

Schwab, G.O., R.K. Frevert, T.W. Edminster, and K.K. Barnes. 1966. *Soil and Water Conservation Engineering.* John Wiley & Sons, Inc., New York.

SCS Soils-5, 1993. *Database* USDA from EarthInfo, Inc., 5541 Central Avenue, Blulder, CO 80301

Sharpley, A. N. and Williams, J. R. eds. (1990a). *Erosion/productivity impact calculator: 1. Model documentation*. U. S. Dept. of Agric., Washington, DC, Tech. Bul. 1768.

Sharpley, A. N. and Williams, J. R. eds. (1990b). *Perspectives*. EPIC-Erosion/Productivity Impact Calculator, 1. Model Documentation, U.S. Dept. of Agric., Agric. Tech. Bul. No. 1768.

Sharpley, A. N., Jones, C. A., and Williams, J. R. (1990). *The nutrient component of EPIC*. EPIC-Erosion/Productivity Impact Calculator, 1. Model Documentation, U.S. Dept. of Agric., Agric. Tech. Bul. No. 1768.

Sharratt, B., Voorhees, W., McIntosh, G., and Lemme, G. (1998). *Persistence of soil structural modifications along a historic wagon trail.* Soil Sci. Soc. of Am. J., 62, 774-777.

Simunek, J., K. Huang, M. Sejna, and M. T. van Genuchten. 1997. *The HYDRUS-1D software package for simulating the movement of water, heat, and multiple solutes in variably saturated media, version 1.0*. U.S. Salinity Laboratory, USDA, ARS, Riverside, CA.

Smith, S. J., Nicks, A. D., and Sharpley, A. N. (1990a). *Estimation of soil pH changes in EPIC*. EPIC-Erosion/Productivity Impact Calculator, 1. Model Documentation, U.S. Dept. of Agric., Agric. Tech. Bul. No. 1768.

Smith, S. J., Sharpley, A. N., and Nicks, A. D. (1990b). *Evaluation of EPIC nutrient projections using soil profiles for virgin and cultiated lands of the same soil series*. EPIC-Erosion/Productivity Impact Calculator, 1. Model Documentation, U.S. Dept. of Agric., Agric. Tech. Bul. No. 1768.

SSSA. 1996. *Glossary of Soil Science Terms*. Soil Science Society of America, Madison, WI.

SSSA Book Series: (Soil Science Society of America, 677 South Segoe Road, Madison, WI 53711)

1. Dixon and Weed, 1989. *Minerals in soil environments.*
2. Cheng, 1990. *Pesticides in the soil environment: processes, impacts, and modeling*.
3. Westerman, 1990. *Soil testing and plant analysis*.
4. Mortvedt, et al., 1991. *Micronutrients in Agriculture.*
5. Klute, 1986. *Methods of soil analysis: physical and mineralogical methods, Part 1*.
6. Weaver, et al., 1994. *Methods of soil analysis: microbiological and biochemical properties, Part 2*.
7. Sparks, 1996. *Methods of soil analysis: chemical methods, Part 3*.
8. Dane and Topp, 2002. *Methods of soil analysis: physical methods, Part 4*.
9. Power and Dick, 2000. *Land application of agricultural, industrial, and municipal by-products*.
10. Dixon and Schulze, 2002. *Soil mineralogy with environmental applications.*

Steiner, J. L., Williams, J. R., and Jones, O. R. (1990). *Evaluation of EPIC using a dryland wheat-sorghum-fallow crop rotation*. EPIC-Erosion/Productivity Impact Calculator, 1. Model Documentation, U.S. Dept. of Agric., Agric. Tech. Bul. No. 1768.

Stewart, B. A. and D. R. Nielsen (eds.). 1990. *Irrigation of Agricultural Crops*. Agronomy Monograph No. 30, Am. Soc. of Agronomy, Crop Sci. Soc. of Am., and Soil Sci. Soc. of Am., Madison, WI.

Suter, G. W., R. J. Luxmoore, and E.D. Smith. 1993. *Compacted Soil Barriers at Abandoned Landfill Sites Are Likely to Fail in the Long Term*, J. Environ. Quality, 22 (2): 217-226

Taylor, H. M. (1967). "*Effects of tillage-induced soil environmental changes on root growth*". Conference Proceedings: Tillage for Greater Crop Production, ASAE Publication PROC-168. ASAE, St. Joseph, MI,

Taylor, H. M., Robertson, G. M., and Parker, J. J., Jr., (1966). *Soil strength-root penetration relations for medium to coarse-textured soil materials*. Soil Sci., 102, 18-22.

Timlin, D. J., Ahuja, L. R., and Heathman, G. C. (1998). *Preferential transport of a bromide tracer applied in a pulse of ponded water.* J. Environ. Qual., 27, 505-514.

Tolk, J. A., T. A. Howell, and S. R. Evett. 1998. *Evapotranspiration and yield of corn grown on three High Plains soils.* Agron. Jour. 90:447-454

Tolk, J. A., T. A. Howell, J. L. Steiner, and S. R. Evett. 1997. *Grain sorghum growth, water use, and yield in contrasting soils.* Agricultural Water Management, Elsevier 35: 29-42.

Unger, P. W. (1979). "*Effects of deep tillage and profile modification on soil properties, root growth and crop yields in the United States and Canada*". Geoderma, 22, 275-295.

Unger, P. W. and F. B. Pringle. 1981. Pullman Soils: Distribution, importance, variability and management. Texas Agric. Exp. Station, B-1372. 23 pp.

Unger, P. W. (1993). "*Residual effects of soil profile modification on water infiltration, bulk density, and wheat yield*". Agron. J., 85, 656-659.

U.S. EPA. 1991. *Design and Construction of RCRA/CERCLA Final Covers*. Washington, D.C.; EPA/625/4-91/025.

U.S. EPA. 1993. *Presumptive Remedy for CERCLA Municipal Landfill Sites*. Washington, D.C.: EPA Document No. 540-F-93-035.

USEPA. 1996. *Application of the CERCLA Municipal Landfill Presumptive Remedy to Military Landfills.* EPA/540/F-96-020. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency.

van Genuchten, M. T., F. J. Leij, and S. R. Yates. 1991. *The RETCcode for quantifying the hydraulic functions of unsaturated soils.* EPA/600/2-91/065, U.S. Environmental Protection Agency, Washington, DC.

Vogel, T., K. Huang, R. Zhang, and M. T van Genuchten. (1996). *The HYDRUS code for simulating one-dimensional water flow, solute transport and heat movement in variably-saturated media.* Research Report No. 140, U. S. Salinity Laboratory, Agricultural Research Service, USDA, Riverside, CA.

Walker, S. E., J. K. Mitchell, M. C. Hirschi and K. E. Johnsen. (2000). *Sensitivity analysis of the root zone water quality model.* Trans. Of the ASAE 43: 841-846.

Warren, R. W., T. E. Hakonson, and K. V. Bostik. 1997. *The Hydrologic Evaluation of Four Cover Designs for Hazardous Waste Landfills.* In: Reynolds, T. D., and R. C. Morris (Eds.), Landfill Capping in the Semi-Arid West: Problems, Perspectives, and Solutions. Environmental Science and Research Foundation, Idaho Falls, ID.

Watts, D. G., N. R. Fausey and D. A. Bucks. (1999). *Root Zone Water Quality Model*. Agron. Jour. 91: 169-170.

Weand, B.L., J.D. Horin, V.L. Hauser, D.M. Gimon, M.D. Gill, M. Mehta, and D.J. Casagrande. 1999. *Landfill Covers for Use at Air Force Installations*. Air Force Center for Environmental Excellence, Brooks AFB, TX. Available at: http://www.afcee.brooks.af.mil/er/ert/landfill.htm.

Williams, J. R., P. T. Dyke, W.W. Fuchs, V. W. Benson, O. W. Rice and E. D. Taylor. 1990. *EPIC--Erosion/Productivity Impact Calculator: 2 User Manual.* A. N. Sharpley and J. R. Williams, ed's. U.S. Department of Agriculture Technical Bulletin No. 1768. 127 pp.

Wu, L., W. Chen, J. M. Baker and J. A. Lamb. (1999). *Evaluation of the root zone water quality model using field-measured data from a sandy soil*. Agron. Jour. 91: 177-182.

WXgen. 1999. *Weather Parameter Generation Software* (WXpm7240.exe) available from Dr. J. R. Williams at (williams@brcsun0.tamu.edu) and described in Sharpley and Williams, 1990a.

WXparm. 1999. *Weather Parameter Generation Software* (WXGN7240.exe) available from Dr. J. R. Williams at (williams@brcsun0.tamu.edu) and described in Sharpley and Williams, 1990a.

Zacharias, S., C. D. Heatwole, and C. W. Coakley. 1996. *Robust quantitative techniques for validating pesticide transport models*. Trans. ASAE, 39: 47-54.

Zhang, R. and M. T. van Genuchten. 1994. *New models for unsaturated soil hydraulic properties*. Soil Science, vol 158 (2): 77-85.

Appendices

Appendix A

Acronyms

AET	actual evapotranspiration
AFCEE	Air Force Center for Environmental Excellence
ARS	Agricultural Research Service
ASCE	American Society of Civil Engineers
AWC	plant available water content
CEC	cation exchange capacity
CN	curve number
CRM	coefficient of residual mass
EF	modeling efficiency
EPA	Environmental Protection Agency
EPIC	Environmental Policy Integrated Climate
ET	evapotranspiration
FC	field capacity
HELP	Hydrologic Evaluation of Landfill Performance
I	irrigation
IGWMC	International Groundwater Modeling Center
INRA	Institut National de la Recherché Agronomique
L	lateral flow
MAD	median absolute deviation
MdAE	normalized median absolute error
Mg	megagram
NAEW	North Appalachian Experimental Watershed
NRCS	Natural Resource Conservation Service of the USDA
P	precipitation
PET	potential evapotranspiration
PRK	deep percolation
Q	surface runoff
RCRA	Resource Conservation and Recovery Act
REF	robust modeling efficiency
RMSE	normalized root mean square error
RZWQM	Root Zone Water Quality Model
SCS	Soil Conservation Service of the USDA
SSSA	Soil Science Society of America
SW	soil water
USDA	U.S. Department of Agriculture
WP	(permanent) wilting point

Appendix B

Equations

$$P + I = ET + Q + L + \Delta SW + PRK$$ ....EQUATION 1

$$error = (P + I) - (ET + Q + PRK + \Delta SW)$$ ....EQUATION 2

$$MAD = 1.4826 \times median(| x_i - x_m |: i = 1,2...,n)$$ ....EQUATION 3

$$error = \left[\frac{P_m - O_m}{reference} \right] \times 100$$ ....EQUATION 4

$$RMSE = \frac{100}{\overline{O}} \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}}$$ ....EQUATION 5

$$EF = \frac{(\sum_{i=1}^{n} (O_i - \overline{O})^2 - \sum_{i=1}^{n} (P_i - O_i)^2)}{\sum_{i=1}^{n} (O_i - \overline{O})^2}$$ ....EQUATION 6

$$CRM = \frac{\left(\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i \right)}{\sum_{i=1}^{n} O_i}$$ ....EQUATION 7

$$MdAE = median(|O_i - P_i| : i = 1,2,...n) \times \left(\frac{100}{O_m} \right)$$ ....EQUATION 8

$$REF = \left[\frac{(median(|O_i - O_m| : i = 1,2,...n) - median(|O_i - P_i| : i = 1,2,...,n))}{median(|O_i - O_m| : i = 1,2,...n)} \right]$$ ....EQUATION 9

Appendix C

Climate Characteristics

Today, conventional landfill cover design is relatively simple because the regulations contain design specifications. However, there are no specifications within the regulations to control or assist with the design of alternative landfill covers; therefore, they require conventional engineering evaluation and design. Climate and its effect on the performance of alternative landfill covers are important factors in the selection of the cover type and its design.

Regional climate should be the first consideration when evaluating the suitability of an alternative landfill cover for a site. If the regional climate appears to be compatible with the requirements of the alternative cover, then site characteristics should be examined to determine if there are important differences between the site climate and the regional climate. The site climate will be similar to that at nearby stations for most of the country. However, site and regional climate data may differ substantially for sites near mountains, in valleys, in the rain shadow of coastal mountains, or near the coast.

An adequate measurement of the climate at a site requires the longest available record and should contain a minimum of 20 years of data. The importance of long records can be illustrated by the annual rainfall from Coshocton, Ohio: while the 35-year average annual rainfall is 37 inches, one 5-year period averaged 88 percent of the overall average (32.5 inches) and another averaged 115 percent (42.4 inches). Clearly, a short record may not accurately describe the climate at a site and should not be used for design. However, short climatic records may be used to evaluate differences between the site and nearby stations during equivalent time periods. Based upon the degree of correlation, the long-term records from nearby stations may then be modified and used at the site.

Site-specific climatic factors that are important to selection of landfill cover type and to design of evapotranspiration (ET) landfill covers include daily precipitation values, maximum and minimum temperature, relative humidity, total solar radiation, and daily wind run. If all of the data are not available, one can make useful—but less accurate—estimates of cover performance using just the daily precipitation values and the maximum and minimum temperatures.

As stated above, the first step in evaluating a site to determine the kind of landfill cover required should be a quick and inexpensive assessment of the regional climate. Such an assessment provides a simple and low-cost determination of the potential for an alternative ET landfill cover at the site. The Air Force Center for Environmental Excellence commissioned a generic assessment of the suitability of the ET landfill cover based on regional climate for the continental United States (Hauser and Gimon, 2001). A summary of that assessment is provided below.

1. Initial assessment—background

ET landfill covers contain a layer of fertile soil covered by native grasses, but they have no barrier layer (Figure C-1). The soil acts as a water reservoir, and natural evaporation from the soil and plant transpiration empty the soil-water reservoir before water can infiltrate into the waste. Both potential and actual ET (PET and AET) are important design criteria because they determine the effectiveness of the ET landfill cover. The PET is the maximum amount of water that plants and evaporation can remove from the soil. The AET is less than PET and indicates how the cover may actually perform in the environment of the site. The concept and principles of ET landfill covers were previously verified and are more completely described in Hauser et al., (2001). Additional detail regarding their use, design and limitations are contained in Weand et al., (1999), Hauser et al., (1999), Boyer et al., (1999), and Gill et al., (1999).

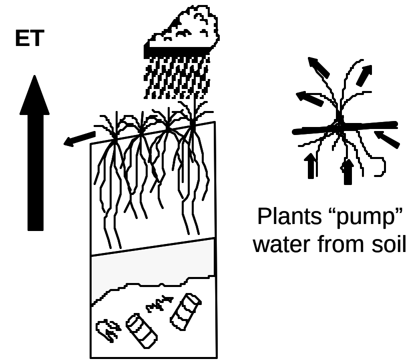

Figure C-1. ET Landfill Cover

The water balance is an accounting of all water entering and leaving an ET landfill cover—a mass balance (see Figure C-2). The source for infiltration is both precipitation and irrigation, if applied. ET moves the majority of the incoming water back to the atmosphere. The second largest loss of water is by surface runoff. Change in stored soil-water, lateral movement, and deep percolation are also included in the water balance for an ET landfill cover. However, over the period of several months or a year, the sum of soil-water storage change and lateral soil-water movement tends toward zero for an ET landfill cover. Deep percolation may be zero or greater, depending on climate, soil, and plant growth, as well as their interactions at the site. Where the water table is near or in the waste and there is no landfill liner, capillary rise from the water table and possible change in groundwater storage may be important components of the water balance; normally, these components do not apply or are very small for ET landfill covers. Because a primary purpose of any landfill cover is to minimize infiltration of water into the waste, evaluation and design of an ET landfill cover requires assessment of possible deep percolation below the root zone; it is a small but important part of the water balance.

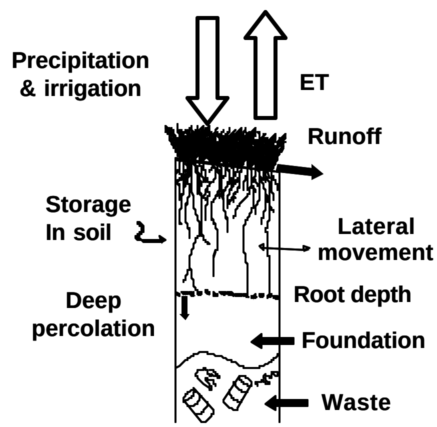

Figure C-2. Water Balance for an ET Landfill Cover

While each water balance element should be evaluated during landfill cover design for a specific site, it is possible to make a preliminary assessment of climate at the site to determine possible suitability of an ET cover. This can be done by evaluating the largest element of the water balance, PET. If the PET is larger than the annual precipitation, it is highly likely that the ET landfill cover will meet the requirements for a cover at the site.

2. Initial Assessment—Summary

Hauser and Gimon (2001) evaluated PET at 60 sites widely dispersed within the continental United States (Figure C-3). They used the Environmental Policy Integrated Climate (EPIC)[1] model described by Sharpley and Williams (1990a) and Williams et al., (1990) to estimate PET for each site. The EPIC model is a comprehensive model that was extensively tested and meets the requirements for PET estimation (Nicks et al., 1990; Cole and Lyles, 1990; Sharpley et al., 1990; Smith et al., 1990a and 1990b; Favis-Mortlock and Smith, 1990; Steiner et al., 1990; Cooley et al., 1990; Kiniry et al., 1990; and Sharpley and Williams, 1990b). In addition, Meisinger et al., (1991) and Chung et al., (1999) evaluated the performance of the EPIC model and its estimate of deep percolation with both lysimeter data and watershed scale measurements. The results of their work demonstrate that EPIC satisfactorily estimated the water balance, including deep percolation below the plant root depth. The EPIC model is in use by the U.S. Department of Agriculture (USDA) throughout the United States.

Figure C-3. Sites Where PET Was Estimated

The PET estimation method developed by Penman-Monteith is the most accurate of 20 methods tested by Jensen et al., (1990); however, it requires a complete climate data set, including daily wind run and relative humidity. These data were unavailable for many locations. Therefore, Hauser and Gimon (2001) used the Priestly-Taylor method for locations east of 100^{o}W longitude and the Hargreaves method west of that line. Jensen et al., (1990) found that these methods provide accurate estimates when used as described above, and do not require wind and humidity data. They used the EPIC model to generate a 100-year estimate of daily climate; from that, they were able to estimate daily PET values for each location shown in Figure C-3. Hauser and Gimon (2001) estimated the ratio of PET to precipitation for each location; the results are summarized in Figure C-4.

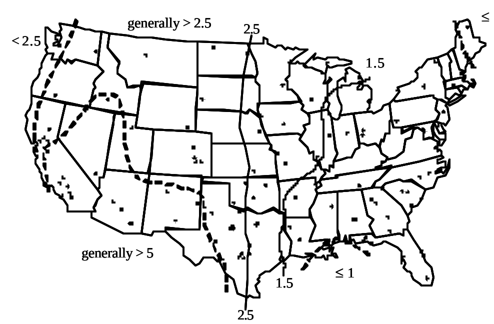

Figure C-4. Ratio of PET to Precipitation

The ratio of PET to precipitation is greater than one for almost all of the continental United States (Figure C-4). Where the ratio is less than 1.2, careful evaluation and matching of results with requirements for the landfill cover are required. Therefore, the ET landfill cover passes this first test for most sites; the exceptions are primarily coastal sites with high precipitation and cool cloudy weather most of the year or sites with long and cold winters. The landfill owner may choose to make an inexpensive, site-specific assessment of the PET to precipitation ratio.

---

1 Name change, personal communication from Dr. J. R. Williams, Texas Agricultural Experiment Station, Temple, TX

3. Climate Statistics for Estimation of Future Daily Weather Data

After determining whether the ET landfill cover is appropriate for a site based on a regional analysis, the next step is to evaluate possible cover designs and estimates of possible future performance of the cover to determine whether it will meet the requirements for the site. The design should be based on estimated future extreme events. Few climate records contain accurate data for more than 60 or 70 years, and they may not reveal extremes that are important to ET cover design. Likewise, it is not known whether the existing data represent above average or below average conditions that might be demonstrated by longer records if they were available for the site.

An acceptable alternative in the design process is to use the longest record available to generate statistics representing the climate at the site. By using these statistics and a random number generator, very useful estimates of possible future performance can be made (Sharpley and Williams, 1990a, and Williams et al., 1990). The generated data possess the same statistical properties as the measured data; however, because they randomly estimate a much longer record, they are likely to demonstrate more extreme events than were measured at or near the site. The USDA developed a climate generator for the EPIC model; this climate generator is also used in other models. Monthly statistics required for generation of daily climate data within the EPIC model (Sharpley and Williams, 1990a and Williams et al., 1990) include the following:

- Monthly average maximum daily temperature
- Monthly average minimum daily temperature
- Monthly standard deviation of daily maximum temperature
- Monthly standard deviation of daily minimum temperature
- Average total monthly precipitation
- Monthly standard deviation of daily precipitation
- Monthly skew coefficient for daily precipitation
- Monthly probability of wet day after dry day
- Monthly probability of wet day after wet day
- Monthly average number of days of precipitation

The EPIC model utilizes these statistics derived from local data to generate daily values of precipitation, maximum and minimum temperature, solar radiation, humidity, and wind speed; these values are used in turn to estimate PET for each day.

The HELP model can also generate daily simulated climate data, but uses a smaller set of input data. The climate statistics used for daily climate generation in HELP are:

- Monthly total precipitation
- Monthly average mean daily temperature
- Monthly total solar radiation

For generation of PET, HELP also requires the input of quarterly average humidity for the site.

4. Evaluation of Model-Generated Future Climate

Model-generated climate data should be evaluated to determine whether it is adequate for design. The following example illustrates the process. Annual values of precipitation, annual maximum one-day precipitation, and annual maximum daily temperature usually fit a normal distribution curve. It is therefore, relatively easy to estimate the probability for these annual extremes of both measured and model estimated data for comparison. The result from one model evaluation follows.

Precipitation is the most important climate parameter used to estimate PET and landfill cover performance. Figure C-5 compares annual precipitation measurements with estimates by EPIC that employ monthly statistics derived from 45 years of measured annual precipitation for Stapleton Airport, Denver, Colorado. The agreement between measured and estimated annual precipitation is good. These data illustrate how a relatively short record (45 years) may be used to make realistic estimates of likely precipitation for 100 years in the future. These data also indicate that the Stapleton annual precipitation record fits the normal distribution because the EPIC estimates are based on the assumption of normality. It is likely that additional measurements at Stapleton would produce a record that is statistically similar to the data generated by the EPIC model.

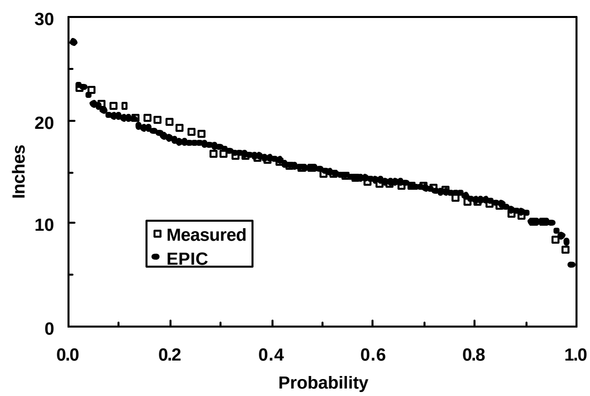

Figure C-5. The probability for measured and estimated annual precipitation at Stapleton Airport, Denver, Colorado.

For all of the data generated by the EPIC model, only one estimated yearly precipitation amount is substantially larger than the greatest measured value and only one is smaller (see Figure C-5). Therefore, it appears that the existing record can provide useful statistics for design. The cover should be designed and built so that it is adequate to satisfy requirements during an extreme event (one or several days) and in an extreme year, such as the year with 27.6 inches of model-generated precipitation (Figure C-5).

Appendix D

Surface Water Runoff

Surface water runoff normally is the second largest part of the outgoing water in the hydrologic water balance for evapotranspiration (ET) landfill covers and it is therefore important to the design process. Water leaving the site as surface runoff reduces the volume that must be stored within the cover. Errors in estimating the daily amount of surface runoff will result in erroneous estimates of cover performance as measured by deep percolation of water below the cover. This brief discussion of principles of surface runoff generation are directed to the problem faced by a design engineer who intends to design an ET landfill cover for a specific site where daily precipitation, air temperature, and limited soils data are likely to be the only hydrologic data available. Typically, there are no applicable surface runoff measurements against which the designer may test possible models of cover performance for a site, so surface runoff must be estimated.

1. Factors affecting surface runoff

Surface runoff can begin only after (1) rainfall or snowmelt fill storage by plant interception, surface storage and ponding, and (2) the rainfall rate exceeds the soil infiltration rate. It is not possible to discuss all aspects of surface runoff here; excellent sources for technical details include Chow et al., (1988), Linsley et al., (1958) and ASCE Manual 28, (1996). This section discusses key factors to consider during ET landfill cover design and construction. Factors affecting surface runoff are listed in Table D-1.

Table D-1. Factors affecting amount and rate of surface runoff from ET landfill covers.

Soil	Surface	Other factors
Infiltration rate	Surface crust and tilth	Rainfall intensity
Water content	Plant type (sod or bunch grass, etc.)	Time of occurrence of high intensity
Particle size distribution	Cover density	Storm duration
Frozen soil	Growth rate	Interception by plants
Bulk density	Stage of annual growth cycle	Soil surface depressions
Clay mineralogy	Biomass production	Litter on the soil surface
Macro porosity	Roughness and storage	Land slope

Surface runoff from ET landfill covers is derived from the precipitation that does not infiltrate into the soil surface; it results from several factors. Some factors affect each other, and runoff is controlled by complex interactions both before and during a storm.

Robust stands of sod grasses in a humid climate may provide substantial surface storage of rainfall, impounding the water until it has a chance to infiltrate, - thus reducing runoff. However, a robust stand of bunch grasses at arid or semi-arid sites may have substantial areas of bare soil between bunches. Bare ground between bunches of grass at arid sites typically develops a substantial surface soil crust, thus increasing the potential for surface runoff. A similar situation may develop under tree or shrub canopies.

Land slope is often cited as an important variable in estimates of surface runoff. The primary effect of land slope is its influence on surface water detention and storage in puddles and ponds. Because a requirement for any landfill cover is to reduce water infiltration into the waste, ET landfill covers should be built with smooth soil surfaces and land slopes between 2.5 and 8 percent. Figure D-1 contains 100-year estimates of average annual surface runoff by the Soil Conservation Service (SCS) method (discussed below) for a loam soil at Cheyenne, WY. The difference in estimated annual runoff is only 0.2 inches between land slope of 2.5 and 10 percent. The adjustments for slope within the SCS method assume average soil roughness and surface ponding. A correctly built ET landfill cover (smooth surface) should provide substantially less surface storage than assumed within the SCS runoff method. The actual effect of surface slope should be less for an ET cover than that shown in Figure D-1. Land slope should have a small effect on the surface runoff amount from correctly built ET landfill covers.

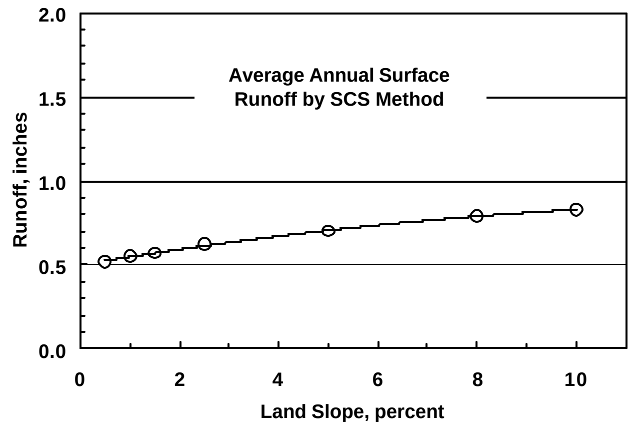

Figure D-1. Effect of land slope on annual surface runoff.

Additional important factors affecting runoff volume include the length of the storm and time during the storm when high intensity rainfall occurs. Figure D-2 illustrates the effect of soil type and rainfall events on possible surface runoff from dry soil. The data shown in Figure D-2 were created to simulate possible events. The two rainfall events have similar duration (90 minutes) and total rainfall amount (3.5 cm), but differ in the time during the storm when high rainfall intensity occurs. Figure D-2 contains estimates of soil infiltration rate generated with the Philip equation from one set of field measured infiltration data for initially dry soil (Linsley et al., 1958). The time of high rainfall intensity during the storm may substantially influence the amount of surface runoff. As shown in Figure D-2, the volume of runoff from clay soil is usually larger than for sandy loam soil for similar storms. This is caused by the greater infiltration rates of sandy loam soil than for clay soil.

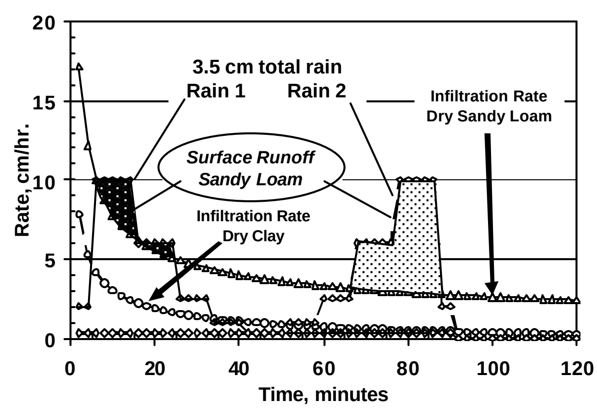

Figure D-2 Affect of storm type on runoff volume with initially dry soil.

The soil-water content at the beginning of a rain storm has a large effect on the infiltration rate and hence the amount of surface runoff. Figure D-3 shows estimates similar to those in Figure D-2, except the infiltration curves were derived from measurements on soil that was wet before the test. These data illustrate the possible influence of soil-water content on surface runoff. In this case, the time of high intensity rainfall within the storm causes a smaller difference in runoff amount between the two storm types than for the dry soil example shown in Figure D-2.

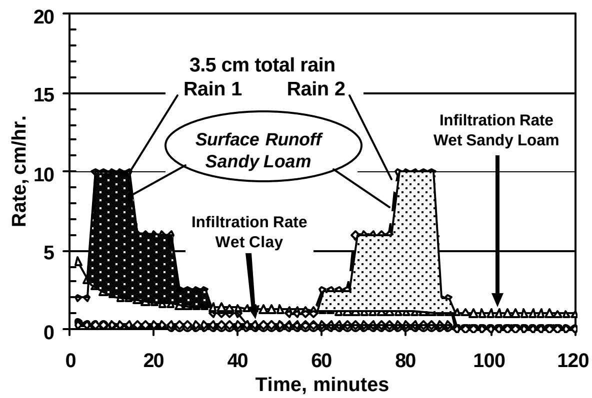

Figure D-3 Affect of storm type on runoff volume with initially wet soil.

The Philip equation (Philip, 1954) was used above to illustrate the effect of infiltration rate and storm type on surface runoff. The equation is:

$$I = \frac{bt^{-0.5}}{2} + a \quad \text{Where}$$

I = infiltration rate
t = time, and
a & b = empirical coefficients fitted to experimental data

Philip derived the equation from theoretical principles; however, the derivation required numerous assumptions and its use requires fitting the coefficients a and b to measured data. Although Philips equation fits many experimental data, this simple equation can not show the numerous changes in the infiltration rate that will occur during a rain event and it may or may not represent field infiltration in this form.

Several factors presented in Table D-1 were not discussed here, but may be important to evaluation of surface runoff for ET landfill cover design. Please refer to the references cited above for additional information.

2. Model estimates of surface runoff

Adequate design of an ET landfill cover requires estimates of the peak amounts of water that must be stored in the soil of the ET cover. Required soil-water storage in the cover is directly related to surface runoff. There are at least three ways to estimate surface runoff in models: (1) minute-by-minute amounts (instantaneous), (2) annual or monthly values, or (3) one day amount.

Because rainfall rate and soil infiltration rate vary minute-by-minute during a storm or snowmelt event, estimates of runoff with a small time-step within a model is desirable. These estimates require minute-by-minute rainfall and melt rates as input to the model and an accurate method to predict the corresponding infiltration rate into the soil. However, instantaneous rainfall intensity data of adequate record length are not available for most landfill sites.

Annual or monthly values of runoff may be estimated. The largest amount of soil-water required to be stored by an ET cover may remain in the cover soil for a day or less. This is true because the water volume held in storage within the soil may be reduced by ET on the first day following a precipitation event. Therefore, the one-day peak water storage is much larger than peak annual or monthly values. Annual or monthly estimates of runoff have little use in design of ET landfill covers.

Models are available to estimate all parameters, including surface runoff, in the hydrologic water balance on a daily time-step. Within a few minutes or tens of minutes after rainfall stops, the rate of water movement within the soil may be an order of magnitude, or more, smaller than rainfall or snowmelt rates. Therefore, an acceptable alternative is to design ET covers with available models that work on a daily time-step.

3. *The SCS method*

The Soil Conservation Service[2] of the U. S. Department of Agriculture developed the "SCS curve number method" for estimating surface runoff volume (SCS, 1972). In this discussion it will be called the SCS method. The equations employed by the SCS method are:

$$Q = (P - 0.2S)^2 / (P + 0.8S) \qquad (1)$$

Where

Q = runoff depth, inches (Q=0, if P<0.2S),

P = rainfall depth, inches

S = potential maximum rainfall retention after runoff begins, inches

Equation 1 assumes that initial rainfall abstraction = 0.2S. The parameter S is related to the curve number (CN) by:

$$CN = 1000/(10 + S) \text{, if S is in inches} \qquad (2)$$

The SCS developed the CN concept to estimate extreme-event, design discharge. Extreme events were defined as runoff amounts resulting from large storms having 10 to 50 year return periods. The CN values may be estimated from tables provided by the SCS (SCS, 1972) and in other publications developed since 1972. Estimation of the CN requires the hydrologic soil group assigned by the SCS soil surveyors, plant cover, and land treatment. CN II is the usual design curve number and represents "average" antecedent watershed soil-water conditions. The antecedent soil-water content is assumed related to rainfall on 5 days preceding the event. CN I and CN III represent the dry and wet antecedent soil-water conditions, respectively.

The parameters CN I and CN III may be estimated from CN II by the following equations:

$$CN(I) = \frac{4.2CN(II)}{10 - 0.058CN(II)} \text{, and}$$

$$CN(III) = \frac{23CN(II)}{10 + 0.13CN(II)}$$

[2] The Soil Conservation Service (SCS) was renamed Natural Resource Conservation Service (NRCS)

The original, and still widely used, database of curve numbers was derived primarily from runoff measurements in humid or sub-humid regions of the USA because they were the data available to the developers of the method. Users of the method have found that it provides best runoff estimates east of the Rocky Mountains in the USA, but less accurate estimates west of the Rocky Mountains.

Hauser and Jones (1991) derived CN's for the more arid Texas High Plains from a 32-year long record of runoff measurements from farm size fields west of Amarillo, Texas. Annual precipitation at the site is about 19 inches per year. They reported *"The CN's for wheat and sorghum should be 79 and 82 respectively (handbook CN are both 80). The single handbook CN for fallow (90) is too high; it should be 77 for fallow after wheat and 82 for fallow after sorghum."* Their work demonstrates the need for caution in applying the CN method under dry conditions.

Although the SCS CN method was derived to estimate extreme events (i.e. annual maximum storm rainfall, etc.) it is widely used to estimate runoff for all storm events regardless of frequency of occurrence and frequently used for daily runoff estimates. Extreme events as defined by the SCS could extend over more than one day.

The basic SCS CN method was improved and included within the model now called "Environmental Policy Integrated Climate" (EPIC) model (J. R. Williams[3]). The EPIC model uses the improved SCS runoff model to estimate runoff amount (Sharpley and Williams, 1990a & b and Williams et al., 1990).

Both the EPIC and HELP models use the SCS CN method.

4. Infiltration equation methods used to estimate surface runoff

Several methods and computer programs were developed to estimate infiltration rate. Some of them have been used with rainfall intensity data to estimate surface runoff amount. ASCE Manual 28 (1996) presents and discusses the empirical Kostiakov, Horton, and Holtan infiltration equations. Green and Ampt, Philip, Morel-Seytoux, Kanji, and Smith and Parlange developed approximate, empirical infiltration equations based on theory (ASCE Manual 28, 1996).

The Green-Ampt infiltration equation (ASCE Manual 28, 1996) is a popular approximate model utilizing Darcy's law. The equation is:

$$I = K(1 + (\Phi - \Theta_i)S_f / F)$$

Where,

I = Infiltration rate, cm/hr

K = effective soil hydraulic conductivity, cm/hr

S_f =effective suction at the wetting front, cm

Φ = soil porosity, cm^3/cm^3

[3] Personal communication, J. R. Williams, 1997.

θ_i = initial soil-water content, cm^3/cm^3

F = accumulated infiltration, cm

This equation assumes a ponded surface so that infiltration rate equals infiltration capacity.

The ASCE Manual 28 (1996) discusses 18 engineering design models that compute surface runoff; some of them use infiltration equations to estimate surface runoff. One of the models used the Richards equation to estimate infiltration. One used the Smith & Parlange infiltration equation and two used an "index". Two models could use either the SCS curve number method or the Green-Ampt infiltration equation. Nine of the models used the SCS curve number method and six used the Green-Ampt infiltration equation. The data indicated that the SCS curve number method and the Green-Ampt infiltration equation are by far the most popular methods for estimating surface runoff in engineering design models.

The usefulness of infiltration equations for estimating surface runoff may be limited by soil crusts that are found on the surface of most soils. Soil crusts on ET landfill covers are likely to control infiltration. Although some models estimate water content of surface soil layers with a one minute time-step, the unknown changes of soil crust properties limit their accuracy.

5. Use of measured data to estimate surface runoff

If available, this may be the best method for determining surface runoff volumes. However, surface runoff data measured for an adequate period of time are seldom available or applicable to the ET landfill cover surface. Hence, measured data is seldom a suitable alternative for design. All of the following requirements should be met by runoff measurements in order for them to be used:

- The soil should be similar to the cover
- The plants on the surface should be similar to expected landfill cover
- The runoff record should be long (greater than 30 years)
- The measurement site should be near the future ET cover and have climate similar to the site

Because these requirements are seldom met, this method is typically not appropriate for consideration.

6. Models without a surface water runoff sub-routine

A few models proposed for use in design of ET landfill covers contain no sub-routine to estimate runoff rate or amount. In this case, the designer is forced to make independent estimates of runoff amount and rate for each day of the design period and use separate models for soil-water and for surface runoff. It is difficult to model the interactions between factors that affect runoff, soil-water storage, and deep percolation in two separate models. Therefore, the use of two models may result in significant errors in runoff estimates and is not recommended.

Appendix E

Soil Characterization and Plant-Soil Interaction

Evapotranspiration (ET) landfill covers control the precipitation falling on the surface by providing adequate water storage capacity in the soil to contain the infiltrating precipitation. Total, potential soil-water storage capacity is controlled by soil properties. The storage capacity available at any instant in time is controlled primarily by the balance between infiltration from precipitation and rate of water removal from the soil by ET. The majority of ET is the result of plant transpiration which should be maximized. ET covers perform best when the primary limitation to plant growth is soil-water content, thus assuring rapid soil drying.

The cover design and construction should optimize soil conditions for water use by plants. This is an important tool and can be used to ensure success of the ET cover. Plant growth and water use are controlled by soil and air temperature, precipitation, solar radiation, wind, humidity, disease, and insect attack; however, while these conditions can be planned for, they can not be controlled by the designer or by construction practice. Other soil properties of the ET landfill cover that are important to plant growth and water use are determined by design and construction practices. After landfill cover completion, plant cover may be changed but soil modification may be impractical. Therefore, good soil design and construction are of utmost importance to the success of the ET cover.

The U.S. Department of Agriculture (USDA) soil textural classification system was developed for use in describing soils in which plants grow (SSSA, 1996 and Hillel, 1998). The USDA system is now universally accepted within the USA. It should be used to describe soils used in ET landfill covers because the effect of soils on plant growth is central to success. Definitions of terms used in the USDA system are readily available in the glossary of terms published by the Soil Science Society of America (SSSA, 1996), in Gee and Or (2002), and in text books such as those written by Hillel (1980 or 1998).

By its very nature, construction of an ET landfill cover modifies the soil used to create the cover. Hence, the construction process offers the opportunity to either (1) place the soil so that it will perform better than before it was moved or (2) damage the soil and greatly reduce the opportunity for success in meeting the requirements for the cover. It is important to understand soil properties that control success and how they may be optimized during cover construction.

Agricultural interests amend existing soil properties to improve productivity; their experience demonstrates the power of knowledge of soil properties and the ability to control them. Similar control of soil properties is easily and economically achieved during ET landfill cover construction at little or no added cost. Soils modified by deep plowing produce more plant biomass, store more plant-available water in the soil profile than the native soil, and allow increased rooting depth and root density (Taylor, 1967; and Unger, 1979). Moreover, plants use water quickly and efficiently from soils modified by deep plowing, and the benefits of deep plowing remain effective for decades (Unger, 1993; Musick et al., 1981; and Allen et al., 1995).

Both subsoil and minespoil have undesirable soil properties for plant production. However, four field-scale soil covers built with subsoil or minespoil produced equivalent or better forage production than undisturbed soil because they were properly modified during placement (Chichester and Hauser, 1991; and Hauser and Chichester, 1989). The improvement in physical and chemical properties of both soils during placement was important to success. There is opportunity for similar improvement in soil during ET landfill cover design and construction.

The modification of soil properties during construction of a landfill cover may be more complete and, thus, potentially more effective than deep plowing. Furthermore, the properties of the soil used in an ET cover may be selected to achieve better results than reported for the minespoil tests mentioned above. Control of ET cover soil properties has potential to enhance cover performance and should add little or nothing to construction cost.

1. Soil Properties

This discussion of soils is limited to the properties that are most important to success of ET landfill covers. Some of the most important properties are listed in Table E-1. Soil properties are more fully described in numerous text books and reference materials, including SSSA (1996), Hillel (1980 and 1998), Carter (1993), and the 10-volume SSSA book series.

Table E-1. Soil properties that govern root and plant growth and are important to design and construction of ET landfill covers.

Basic soil properties	Derived or secondary soil properties	Soil conditions/factors affecting plant growth
Particle size distribution	Soil Strength	Temperature
Bulk density	Water holding capacity	Water content
clay mineral type	Field cap./Wilting point	Oxygen in soil air
pH	Hydraulic conductivity	Toxic substances
Total porosity	Fertility	Ammonia
Percentage large pores	Available nutrient supply	CO_2 from decaying OM
Soil salinity	Tilth	Methane
Soil sodium content	Anions/salinity	Bacteria
Humus content	Aeration properties/ connection between pores	Fungi

Soil Humus Content

Humus (often called soil organic matter) is an important component of soils (SSSA, 1996). It is composed of organic compounds in soil exclusive of undecayed organic matter. Humus is resistant to decay, provides significant cation exchange capacity in addition to that of clay minerals, and improves soil structure. It is commonly believed that large amounts of humus are required for best plant growth; this is not true. Plants grow well in fertile soils that contain little humus (such as soils of the Southern Great Plains and the irrigated deserts of the 11 western states). Manure, compost, and grass clippings are organic matter or materials, but they are not humus. The addition of organic material to soil to improve its properties usually improves soil tilth and fertility, temporarily; but it may not be worth the expense in a landfill cover because most of the added material oxidizes and disappears in a few months or years after which soil properties revert to those of the original soil material.

Harmful Constituents in Soil

Landfill cover soils should be free of harmful amounts of manmade chemicals, oil, and natural salts. The salts of calcium, magnesium, and sodium occur naturally and can create high salinity in the soil solution. Soil salts may raise the osmotic potential of the soil solution high enough to prevent plants from using all of the soil water. In addition to its contribution to soil salinity, sodium can cause deflocculation (i.e., dispersion) of clay particles, thereby causing poor soil tilth.

Soil-Water Holding Properties

The water holding properties of ET cover soils are important to success. Soils that hold much water will achieve the desired water control with a thinner layer of soil than those with low water holding capacity. The water holding properties should be expressed as volumetric water content to make estimates of required cover thickness easier to understand. Important water holding properties include the permanent wilting point, field capacity and plant-available water content; they are defined by the Soil Science Society of America (SSSA, 1996) and quoted below.

- Permanent wilting point: "The largest water content of a soil at which indicator plants, growing in that soil, wilt and fail to recover when placed in a humid chamber. Often estimated by the water content at -1.5 MPa soil matric potential."
- Field capacity: "The content of water on a mass or volume basis, remaining in a soil 2 or 3 days after having been wetted with water and after free drainage is negligible."
- Available water: "The amount of water released between in situ field capacity and the permanent wilting point (usually estimated by water content at soil matric potential of -1.5 MPa). It is not the portion of water that can be absorbed by plant roots, which is plant specific."

While the definitions shown above are scientifically correct, it is impossible to apply these definitions exactly to engineering design of a real cover. However, there are approximations that are sufficiently accurate for good engineering design.

The permanent wilting point is commonly called wilting point and may be estimated from laboratory measurements of soil properties on a pressure plate or similar device. A satisfactory estimate of the wilting point is the laboratory measured water content at -1.5 MPa (-15 atmospheres) pressure. It is important that the soil sample represent the soil to be placed the field.

A satisfactory estimate of field capacity is the laboratory measured water content at -0.03 MPa (-0.3 atmospheres) pressure. The estimate at -0.03 MPa is more conservative for ET landfill cover design than the -0.01 MPa value that is sometimes suggested.

The available water definition above states that this value is plant specific. In addition, the wilting point soil-water content is low where potential ET (PET) is low and high where PET is high; thus PET may affect available water content. However, for ET landfill cover design, the plants that are usually selected will have similar ability to remove water from the soil. A satisfactory approximation to "plant-available-water-capacity" (AWC) is the difference between field capacity and wilting point.

Soil Tilth

Soil tilth is "The physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its impedance to seedling emergence and root penetration." (SSSA, 1996). Good soil tilth significantly improves plant growth; it is controlled by particle size distribution, water content, aggregation of soil particles, and soil bulk density. Unfortunately there are no quantitative measures for soil tilth. However, bulk density, particle size distribution and water content are easily measured and optimum values of each are known.

Soil Bulk Density

The road and building construction industry expresses soil compaction as "percent of standard Proctor". The "standard Proctor" density is specific to a single soil sample and specified water content. The "standard Proctor density evaluates the potential soil strength and other structural properties that may be achieved with given soil materials. It is a useful measurement for road and dam construction and other building activities. The goal is high soil strength. However, in an ET landfill cover, the soil <u>must</u> be weak in a successful soil cover.

The Science Society of America (SSSA, 1996) defines bulk density as: "The mass of dry soil per unit bulk volume. The value is expressed as Mg per cubic meter, Mg m^{-3}." For ET landfill covers, the bulk density should be measured in the field with standard methods, reported, and interpreted as soil bulk density in Mg m^{-3} or as the numerically equivalent gm/cm^3. Soil density is easily controlled in the field by controlling both soil-water content and limiting soil compaction during placement.

Soil Strength Properties

Soil strength is an important physical factor in soils supporting plant growth because excessive strength can reduce or stop root growth (Rendig and Taylor, 1989) and limitations on root growth limit the amount of water removed from the soil. Soil strength is controlled by several factors including bulk density, particle size distribution, and water content. It is possible to control soil bulk density in an ET landfill cover during construction, and if it is controlled within a desirable range, the resulting soil strength is usually satisfactory.

In most soils, plant root growth is reduced when soil bulk density exceeds 1.5 Mg m^{-3}, but values above 1.7 Mg m^{-3} may effectively prevent root growth (Eavis, 1972; Monteith and Banath, 1965; Taylor et al., 1966; Jones, 1983; Timlin et al., 1998; and Gameda et al., 1985). Particle size distribution in the soil combines with soil bulk density to control root growth. Roots usually grow better in sandy soils than in clay at the same density. However, the low water-holding capacity of sandy soils discourages their use in ET landfill covers.

Jones (1983) demonstrated that plant root growth is reduced at soil bulk density greater than 1.5 Mg m^{-3} for most soils, and reduced to less than 0.2 optimum root growth for all soils containing more than 30 percent silt plus clay and having bulk density greater than 1.6 Mg m^{-3}. Grossman et al., (1992) summarized 18 laboratory studies and found that root growth was only 0.2 of optimum for soil bulk density greater then 1.45 Mg m^{-3} except for three soils in which root growth was restricted at soil bulk density of 1.3 Mg m^{-3}. In addition to inhibiting root growth, high values of soil bulk density result in low soil-water-holding capacity because pore space is reduced in compacted, dense soils. Compacted soils have few large pore spaces, thus limiting soil air movement and oxygen diffusion to roots.

Because of the risk of settlement, a minimum bulk density should be established. However, because of the nature of an ET landfill cover, settlement less than 5 percent of the cover thickness is unlikely to create problems. For many soils a minimum bulk density of 1.1 Mg m^{-3}, or less, should produce substantially less than 5 percent cover soil settlement. During cover construction, the principle threat to cover properties is high soil density and not settlement. The soil bulk density should be controlled to values between 1.1 and 1.5 Mg m^{-3} during construction of ET landfill covers.

Soil Aeration Properties

Air-filled porosity in the soil is important because each root requires oxygen, and because during rain or irrigation, these pores become channels for water and air to move rapidly through the soil. Soil pore space includes a range of sizes from extremely small to very large. Small pores contribute little to the movement of air, but much of the water is stored in small pores. In an optimal soil structure, large and small pores are connected so that water and air may move freely and there is a desirable distribution of pore size. Sandy soils tend to have large pore spaces and be well aerated. Clay soils often contain more total pore space than sandy soils, but most of the pores may be small. Excess compaction removes most large pores from soils, thus limiting air and oxygen exchange from the atmosphere to the soil air.

Total pore space and soil bulk density are inversely related as illustrated in the following equation;

Porosity = 1.0 - (soil bulk density/particle density)

[Particle density may be assumed = 2.65 for most soils (Hillel, 1980)]

Dense soils have little pore space and low density soils have higher porosity.

2. Plant Response to Soil Properties

Understanding of important plant requirements is critical to correct selection of materials, design and construction of the soil layer in an ET landfill cover. The success of an ET cover is ensured by optimizing all factors controlling plant growth except for soil-water supply. The goal is to make soil-water content a limiting factor to plant growth several times during each normal growing season. The soil-water reservoir should be empty or nearly so at the beginning of severe or critical events that stress the capacity of the cover to control precipitation. This section summarizes important soil properties that affect plant growth, which in this case emphasizes plant roots, their function, and relation to the soil.

Plant Roots: Water removal from the cover soil is controlled by plant roots, so it is necessary to understand the role of roots in the system and their requirements. Rendig and Taylor (1989) state that plant roots serve many complex functions, including the following:

- Roots provide the plant with water and nutrients absorbed simultaneously from deep and shallow soil layers, from moist and partially dry soil, and from soil zones of different biological, chemical, and physical properties
- Roots provide anchorage for the plant
- Roots and shoots are interdependent. If the top of a plant is pruned to reduce biomass, there is usually a reduction of root mass
- Parts of the root system, particularly small feeder roots, die in response to soil drying or other stresses in a particular layer, while, at the same time, new roots may be growing rapidly in another soil layer. Thus, the distribution of actively growing and functioning roots may change from upper to lower and back to upper soil layers during one growing season

Under optimum conditions, some plant roots may grow 2 cm (0.8 inches) per day; however, for most of the time, limiting factors reduce the rate of root growth below the optimum for the plant in question. Root growth limitations reduce the ability of the plant to extract water and plant nutrients from the soil. Rendig and Taylor (1989) discuss factors that may limit root growth, including the following:

- High soil strength and related physical factors, controlled by:
  - Soil density
  - Particle size distribution
  - Soil-water content
- Unsatisfactory soil pH (note: low pH may be corrected during construction)
- Soil temperature either too high or too low
- Salinity of the soil solution (caused by excess Ca, Mg, Na, and other salts)
- Lack of soil oxygen
- Air-filled porosity in the soil
- Chemical toxicity (e.g., pH, Al, Be, Cd, Pb, Cu, Cr, Fe, Hg, Zn, NH_3, B, and Se)
- Allelopathic toxicants

Root Growth and Distribution: The mass and distribution of living plant roots in soil controls the drying of each soil layer. Figure E-1 illustrates possible root distribution patterns. When all soil layers are adequately wetted, roots often develop as shown for condition 1; the majority of the roots are near the surface. However, as the soil dries from the surface downward later in the season the rooting pattern may shift to the condition shown by 2. During and after drought, most of the active roots will be found deep in the soil profile. Many plant roots die but later regenerate in a given soil layer in response to changes in resources and conditions in each soil layer (Camp et al., 1996; Stewart and Nielsen, 1990; and Merva, 1995).

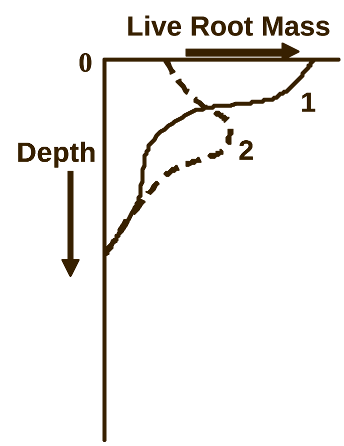

Figure E-1. Root distribution in response to soil water.

It is vital that soil conditions allow rapid growth of new roots in order for the plant cover to remove the stored soil water quickly after a storm. Under favorable conditions, root axes may grow 2 cm/day and root laterals may grow 0.5 cm/day; however, some investigators report growth rates up to 6 cm/day (Russell, 1977). Adverse soil density is a major controller of root growth rate and potential depth of rooting. Many native soils contain layers of high density that limit rate and depth of root growth. However, if the soil is correctly placed in the ET landfill cover, density can be removed as a limitation and good tilth established in the soil. Figure E-2 illustrates the difference in live root mass that may result between a native soil with high density layers and that in a correctly placed ET cover using the same soil placed to achieve optimum soil density. Deep rooting and good soil tilth allow rapid and complete removal of water stored in the cover soil.

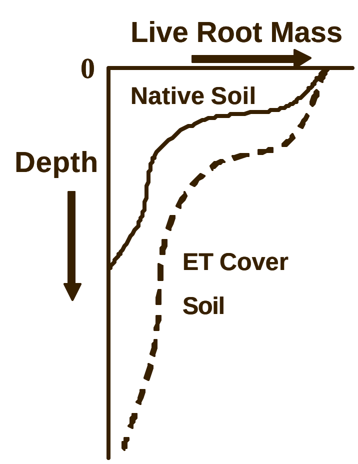

Figure E-2. Root distribution in response to soil tilth & density.

Most native grasses or associated species have the potential to root to depths greater than eight feet. At many natural sites, soil characteristics—rather than the plant potential—limit the rooting depth. It is inexpensive to optimize soil physical properties during ET cover construction. The soil conditions for root growth should be optimized throughout the full depth of the cover at all vegetative landfill cover sites to allow root growth to the bottom of the cover soil.

3. The Physics of Soil-Water Movement

The physics of water movement within the soil is important to an understanding of the principles that govern the performance of a vegetative landfill cover. The modern understanding of water movement in unsaturated soils has been under development for about 150 years, and the development of new concepts continues in the modern era. Henri Darcy (1856) provided the earliest known quantitative description of water flow in porous mediums. Darcy developed an equation for water flow in saturated sand, and modern equations for both saturated and unsaturated flow are based on his early work.

Water held in soils supporting plants, except phreatophytes, exists at negative pressure. Saturated soils have zero or positive water pressure. Most plants can survive saturated soils for very short time periods (consider flooded soils). The negative pressure may be less than minus 30 atmospheres in soil. The water held in plants also is held at negative pressure and plant water pressure may be below minus 40 atmospheres. In order for plants to extract water and the associated nutrients from soil, they must exert a more negative pressure at the root/soil interface than exists in the soil in which they grow. Plants grow best when plant and soil-water pressures are relatively near zero but still negative. At this condition, large soil pores are filled with air but water is readily available to plant roots at peak rates. The physics of water movement in the unsaturated soil of an ET landfill cover is very different from that below the water table where pressures are positive.

It is necessary to understand water flow and soil hydraulic conductivity of unsaturated soil in order to understand the function of an ET landfill cover. The soil hydraulic conductivity

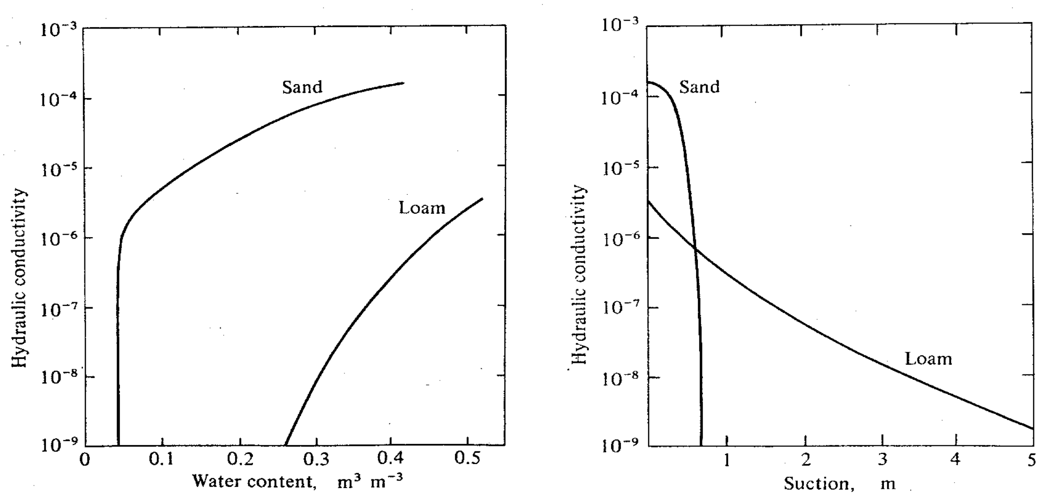

Figure E-3. Hydraulic conductivity of sand and loam soil as a function of soil-water content (left) and of soil-water potential (suction) on the right.

relationships differ greatly between soils; they depend on particle size distribution, soil structure, and on other factors. Figure E-3 presents examples of measured hydraulic conductivity. In the unsaturated soils of an ET landfill cover, hydraulic conductivity may vary over several orders of magnitude. Furthermore, the relationship is different for soils that are increasing in water content, as compared to that in soils that are drying.

Examination of the illustrative data in Figure E-3 reveals the mechanism that allows the ET landfill cover to control water within the cover soil. The soil-water content, in the wetted soil layers, drains to the field capacity quickly when rainfall ends. At field capacity (less than -0.3 atmospheres pressure or about 2 m of suction), the loam soil depicted will have hydraulic conductivity (K) less than 10^{-7} cm/sec. The possible water movement downward in the soil is very small for such low values of K, and the K value decreases rapidly as the soil dries, Figure E-3. Theoretically, and as measured in the field, soil water never stops moving; however, the rate of movement is very small a few hours after precipitation ends. Therefore, for practical purposes water is held in suspension within the soil beginning about two days after rainfall ends.

The currently-used equations for water flow in unsaturated soil are based on the assumption that soils are similar to a bundle of capillary tubes and that water flow can be approximated by the Hagen-Poiseuille equation (Marshall et al., 1996). While it is obvious that the pore space in soil is not the same as a bundle of capillary tubes, the concept has proven highly useful and is currently used in mathematical descriptions of water flow in soil.

The Richards equation: The foregoing discussion and the relationships illustrated in Figure E-3 point out that theoretical estimation of water flow in unsaturated soils is difficult and complex. An equation known as the Richards equation is widely used in research to estimate water flow in both saturated and unsaturated soils. It is also used in software proposed for use in evaluation of ET landfill covers. The derivation of the equation commonly solved in modern models required numerous assumptions. Therefore, the Richards equation is an approximation; however it provides good estimates of flow of liquid water where good estimates of soil hydraulic conductivity are available. Estimates of unsaturated soil hydraulic conductivity for small volumes of soil used in research are difficult. It is more difficult to make accurate estimates of likely field values for a field or complete ET cover. Nevertheless, the Richards equation is used in some models. Hillel (1980) provides this version of the equation:

$$\frac{\partial q}{\partial t} = \frac{\partial}{\partial z}\left(\frac{K\partial q}{C\partial z}\right) - \frac{\partial K}{\partial z} \quad \text{The Richards equation}$$

Where:

θ = Volumetric soil-water content

t = Time

z = Distance

K = Hydraulic conductivity at soil-water content θ

$C = -\partial q / \partial y$ is defined as the specific water capacity, and

ψ = Suction head

During landfill cover design, soil hydraulic conductivity relationships will be needed if the Richards equation is used to estimate water flow in the finished landfill cover soil. The landfill cover soil is likely to be a mixture of several layers of soil, thus its hydraulic conductivity characteristics must be estimated. Cost constraints and uncertainty about whether laboratory measurements represent the finished soil may make it necessary to estimate the soil hydraulic conductivity relationship rather than measure it. Numerous authors have developed methods for estimating the hydraulic conductivity functions from simpler and more easily measured soil parameters. For example, Savabi (2001) employed methods described by 12 different authors to estimate soil hydraulic conductivity in his model evaluation of the hydrology of a region in Florida. Van Genuchten et al., (1991), Zhang and van Genuchten (1994), and Othmer et al., (1991) each developed computer code to estimate hydraulic functions for unsaturated soils.

4. Soil Volume and Cover Depth

After the decision is made to design an ET cover, the first step should be careful inventory of soils available for use in the cover to determine their properties, volume available, distance from the site to the soil resource, and to estimate cost for acquisition and hauling to the site. At this stage the designer should make a preliminary estimate of the performance of a cover utilizing available soil and determine whether it is appropriate to continue with design of an ET cover for the site. After determining that an ET cover is appropriate, followed by complete soil evaluation, it is then possible to design an effective ET landfill cover.

Descriptions that are suitable for initial analysis of soils found near the site are available from official soil surveys of the U.S. Department of Agriculture, Natural Resource Conservation Service (USDA/NRCS) (available at county or state offices). The Land Grant Universities are also a source of soil data for their respective state. The USDA/NRCS soil surveys include aerial photos of each county with individual soil units marked for reference to the data contained in their tables. The user should collect information on the soils that are available within a reasonable haul distance of the landfill site. After the initial evaluation, the user should sample and evaluate the soil in the proposed borrow source.

The following discussion illustrates the use of USDA soil data during planning. Table E-2a-c, contains data abstracted from a USDA/NRCS soil survey for a site on the western edge of the central Great Plains and calculations from those data. Table E-2a contains the raw data copied from the survey. Table E-2b contains the user summary of that data and Table E-2c contains ET landfill cover design data derived from the soil survey data.

The original data (Table E-2a) did not contain field capacity and wilting point estimates, therefore, they were estimated independently to agree with the reported available water holding capacity and the pore space calculated from the measured bulk density. Note that the sum of sand silt and clay in Tables E-2b and c is 100 percent because the coarse material was removed before analyzing the "soil" at the site. The soil contained about 2.5 percent coarse material that does not contribute to water holding properties; therefore, during model evaluation the available water holding capacity of the soil was reduced appropriately.

Similar soil data should be collected for other series that are available near the landfill site. The thickness of soil that may be used for each soil resource will vary with soil properties at the site.

Table E-2a. Data available from the soil survey by the USDA, Natural Resources Conservation Service, for Evanston Loam, map unit 131, Wyoming.

Evanston loam soil	Depth, inches		
Soil Survey Data	0-3	3-15	15-60
USDA Class	Loam	Loam	Loam
Unified Class	CL-ML	CL	CL
Clay, %	15-27	18-35	18-27
% pass, #200 sieve	50-70	55-70	50-65
% pass, #10 sieve	95-100	95-100	95-100
% pass, #4 sieve	95-100	100	100
Bulk Density, Mg/m^3	1.25-1.35	1.3-1.4	1.3-1.4
K, in/hr	0.6-2.0	0.6-2.0	0.6-2.0
AWC[1], cm/cm	0.15-0.18	0.16-0.19	0.15-0.17
pH	6.6-7.8	7.4-7.8	7.4-8.4
Soil organic Matter, %	2-4	1-3	0.5-1
CEC[2], meq/100 g	9-16	11-25	10-16
$CaCO_3$, %	--	--	3-5
Salinity, mmhos/cm	--	0-2	0-2

Table E-2b. Summary of soil survey data for use in design.

Evanston loam soil	Depth, inches		
	0-3	3-15	15-60
Sand/gravel[3], %	2.5	2.5	2.5
Sand, %	40	38	43
Silt, %	39	36	35
Clay, %	21	26	22
Bulk Density, Mg/m^3	1.3	1.4	1.4
AWC[1], cm/cm	0.16	0.17	0.16
pH	7.0	7.6	7.6
Soil organic Matter, %	3	2	0.8
CEC[2], meq/100 g	12	18	13

Table E-2c. Design data derived from a mixture of soil layers by using weighted averages from data in Table E-2b, 0 – 60 inch depth.

Evanston loam mixture		AWC[1], cm/cm	0.16
Sand/gravel[3], %	2.5	Wilting Point, cm/cm	0.16
Sand %	42	Field Capacity, cm/cm	0.32
Silt %	35	CEC[2], meq/100 g	14
Clay %	23	pH	7.6
Bulk Density, Mg/m^3	1.4	Soil organic matter %	1.1

1. AWC = available water holding capacity, cm/cm
2. CEC = Cation exchange capacity, meq/100 g
3. Sand/gravel = Coarse sand, gravel and rocks >2mm in size

Natural soils are usually composed of layers whose material properties vary substantially, Table E-2a. However, these diverse properties often result in superior soils after the layers are completely mixed and placed in an acceptable manner. If the ET landfill cover design is based on mixtures of two or more soil layers, it is important to clearly define the mixture and to know its properties. During construction, the soil should be adequately mixed to achieve the properties required in the design. Adequate mixing may be achieved by wheel loaders or machines similar to trenching machines that cut a uniform volume of soil from each layer in each rotation of the wheel. Other machines should achieve an equal amount of mixing and assure adequate mixing of the soil material.

Table E-3 contains design soil data derived for five soils near a site. The soils were described by the soil texture name associated with the original soil data. The texture name was derived from the surface soil layer and does not represent the entire profile used. The loam 1 and silt loam soils have adequate water holding capacity for use in an ET landfill cover. Both the gravely loam and loam 2 have low water holding capacity and are unsuitable. The silty clay loam is unsuitable because the soil salinity as expressed by the conductivity is too high.

Table E-3. Design soil data derived from a mixture of soil layers, in the 0-60-inch depth. The texture name for each soil was derived from the surface soil layer of the native soil.

Soil Property	Loam 1	Silt Loam	Gravely Loam	Loam 2	Silty Clay Loam
Sand, %	42	22	81	74	7
Silt, %	35	56	6	14	64
Clay, %	23	22	13	12	29
AWC[1], cm/cm	0.16	0.20	0.07	0.08	0.16
CEC[2], meq/100g	14	10	8	8	13
pH	7.6	7.9	7.8	7.5	8.5
Sand/gravel[3], %	2.5	2.5	50	25	0
Conductivity[4], mmhos/cm	0-2	0-2	0-2	0-2	4-8

1. AWC = available water holding capacity, cm/cm
2. CEC = Cation exchange capacity, meq/100 g
3. Sand/gravel = Coarse sand, gravel and rocks >2mm in size
4. Conductivity = Electrical conductivity

A model evaluation of the soils at the site produced an estimate of the daily water balance and deep percolation for each day of the 100-year period modeled. The model evaluation revealed that no water moved below a 2-foot thick cover of the loam soil during the 100-year model period. It also revealed that no water moved below the 1.5-foot thick cover using the silt loam soil during the 100-year modeling period.

The designer may use the required soil thickness estimated by model evaluation, and the surface area of the landfill, to estimate the volume of soil required for an ET landfill cover.

Appendix F

Important Plant Parameters for Design of ET Covers

Estimating the performance of plants on an ET landfill cover requires a daily estimate of plant growth, maturity, dormancy, ground cover, above ground biomass, below ground biomass, water demand, actual water use and other parameters. In addition, the amount of bare soil exposed between plants must be estimated from the plant parameters on a daily basis to permit accurate estimates of evaporation from soil.

Some plant parameters are similar, but others differ substantially between species. The following list identifies several plant parameters that are important to design and performance of ET covers.

- Plant density
- Potential heat units (or a similar system to define stage of plant growth and when the plant achieves maturity, becomes dormant or dies)
- Potential heat units for plant emergence or beginning of growth for perennial plants.
- Biomass-energy ratio
- Biomass-energy ratio decline rate parameter
- Optimal temperature for plant growth
- Minimum temperature for plant growth
- Maximum potential leaf-area-index
- Leaf-area-index decline rate parameter
- Fraction of growing season when leaf area begins to decline
- At least two points on the leaf area development curve.
- Aluminum tolerance (assesses plant growth response to soil pH)
- Maximum stomatal conductance (for use in Penman and Penman-Monteith methods for estimating potential ET)
- Critical soil aeration factor
- Seeding rate (for annual plants)
- Maximum crop height
- Maximum root depth
- Root distribution function
- CO^2 concentration
- Soil nitrogen uptake parameters at emergence or initiation of growth, 0.5 x maturity, and at maturity.
- Soil phosphorus uptake parameters at emergence or initiation of growth, 0.5 x maturity, and at maturity.
- Crop category (annual, bi-annual, perennial, sod, bunch grass, etc.)
- At least two points on the frost damage curve
- Relationship between vapor pressure deficit and biomass-energy ratio
- Ratio of root weight to biomass at emergence
- Ratio of root weight to biomass at maturity
- At least two points on the plant population curve
- Relation between soil-water content and plant growth
- Relation between soil temperature and root growth
- Relation between soil density and root growth

Appendix G

Measured data from Bushland, Texas

The following tables contain measured data from Bushland, Texas, that were available for use in model evaluation.

Table G-1. Properties of the soil in the lysimeters and surrounding field - Bushland, Texas.
Soil properties measured by Unger and Pringle (1981) from a site less than ¼ miles from the lysimeter. Water holding properties are from field measurements in the soil surrounding the lysimeter (Musick, J. T. et al., 1994).

Layer	1	2	3	4	5	6	7	8	9	10
Depth to bottom of layer, m	**0.01**	**0.15**	**0.3**	**0.45**	**0.75**	**1.15**	**1.5**	**1.8**	**2**	**2.3**
Bulk density, Mg/m^3	1.3	1.3	1.5	1.5	1.6	1.6	1.7	1.5	1.5	1.5
Wilting point, v/v	0.12	0.12	0.14	0.17	0.2	0.2	0.2	0.21	0.22	0.22
Field Capacity, v/v	0.37	0.37	0.36	0.36	0.34	0.3	0.31	0.28	0.28	0.28
Sand, %	17	17	15	13	13	15	19	42	42	42
Silt, %	53	53	46	39	40	41	37	21	21	21
pH	6.7	6.7	6.7	6.8	7.2	7.6	7.7	7.7	7.7	7.7
Organic carbon, % (O.M./1.72)[a]	1.2	1.2	0.75	0.75	0.55	0.44	0.23	0.2	0.09	0.09
$CaCO_3$, %	0.2	0.2	0.4	0.5	3.5	3	3	45	25	13
C. E. C.[b], cmol/kg	18.4	18.4	20	20	24	21	17	10	10	10
Coarse frag., (rock > 2 mm), %					0.6	0.3	0.3			

[a] O.M. = organic matter

[b] C. E. C. = cation exchange capacity

Table G-2. Model testing data - Bushland, Texas.

Parameter	Alfalfa	Corn
Years	1996 - 1997	1989 - 1999
Elevation, m (feet)	1164 (3840)	1164 (3840)
Latitude	35.2^o N	35.2^o N
lysimeter - type	Weighing/recording	Weighing/recording
soil	Undisturbed monolith	Undisturbed monolith
dimension (l *x* w *x* d, m)	3x3x2.3	3x3x2.3
surface area m^2 (ha)	9 (0.001)	9 (0.001)
surface slope (%)	0	0
bottom suction	40 in. = aprx. 0.1 atm	40 in. = aprx. 0.1 atm.
precision	0.045 mm	0.045 mm
Soil type	*Pullman clay loam*	*Pullman clay loam*
Wet soil albedo	0.15	0.15
Field capacity[1] (mm)	718	718
Wilting point[1] (mm)	448	448
Available water capacity[1,2] (mm)	270	270
Initial soil-water content (mm)	711	546
Soil hydrologic group	D	D
Crop	Alfalfa	Corn
Plant type	Perennial legume	Warm season, annual grass
Plant population (plants/m^2)	200	6
Maximum leaf-area-index	5	6
Maximum crop height (m)	1.25	2
Maximum root depth[3] (m)	2.3	2.3
Irrigated + precipitation	Yes	Yes

1 Field capacity, wilting point, and available water content are given for entire profile. Field capacity and wilting point for individual layers are in the Bushland soil data table.

2 Available water content = field capacity – wilting point

3 Maximum root depth controlled by lysimeter soil depth.

Table G-3. Average monthly climate data - Bushland, Texas

The long-term averages in this Table were calculated from the 59-year record at the station headquarters of the Conservation and Production Research Laboratory, about ¾ miles from the lysimeter location. The exception is solar radiation, for which there was a 15-year record at station headquarters. The daily rainfall record is complete; however, temperature records were missing for 3 observations. The missing temperature records were simulated by the program WXGEN (from: J. R. Williams, Texas Agricultural Experiment Station, Temple, Texas).

Parameter	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YR
Maximum Temperature, C^{o}	9.62	12.17	16.67	21.70	25.97	30.74	32.49	31.50	27.88	22.64	15.39	10.77	21.46
Minimum Temperature, C^{o}	-6.46	-4.34	-1.09	4.06	9.55	14.84	17.15	16.40	12.16	5.80	-0.91	-4.98	5.18
St. Dev. Max. Temperature	7.85	7.84	7.28	6.39	5.49	4.70	3.40	3.65	5.34	6.03	6.96	7.47	
St. Dev. Min. Temperature	5.38	5.04	4.70	4.27	3.71	3.05	2.29	1.98	3.85	4.23	4.54	4.86	
Precipitation (mm)	12.8	12.8	19.5	27.7	67.5	75.2	67.7	71.5	48.7	38.5	18.5	15.3	475.7
St. Dev. Precipitation	6.28	4.71	6.89	7.97	12.18	12.93	12.64	12.19	13.79	12.30	8.62	7.88	
Skew Factor Precipitation	3.75	2.41	2.85	2.44	2.67	2.43	2.45	1.87	3.36	2.54	4.33	4.04	
Probability Wet Day After Dry	0.074	0.091	0.094	0.115	0.181	0.216	0.175	0.188	0.144	0.094	0.075	0.074	
Probability Wet Day After Wet	0.297	0.335	0.336	0.361	0.418	0.354	0.381	0.344	0.360	0.403	0.350	0.354	
Days Precipitation	2.97	3.39	3.83	4.56	7.37	7.53	6.85	6.90	5.51	4.20	3.10	3.20	59.41
Solar Radiation (MJ/m^2)	11.0	13.5	18.5	22.5	24.1	26.0	26.2	22.5	19.4	15.8	11.6	9.7	18.4
Relative Humidity, fraction	0.55	0.53	0.43	0.43	0.51	0.51	0.51	0.54	0.54	0.52	0.50	0.53	0.51
Wind, m/s	5.61	5.81	6.52	6.33	6.17	6.24	5.35	5.08	5.40	5.35	5.30	5.47	5.72

Table G-4. Daily Climate Data, formatted for EPIC – Bushland, Texas, 1989-1990 Alfalfa, data from weather pen at lysimeter site

Year	Mon	Day	Rad MJ/m^2	Tmax C	Tmin C	Prcp mm	Rhum frac	10m Wind m/s
1989	4	10	23.	7.6	-3.8	0.00	0.66	5.59
1989	4	11	14.	13.9	-2.9	0.00	0.48	8.19
1989	4	12	6.	8.4	1.1	2.29	0.67	5.85
1989	4	13	12.	10.6	2.5	11.94	0.87	4.16
1989	4	14	26.	23.5	2.1	0.00	0.55	4.29
1989	4	15	25.	26.9	5.1	0.00	0.46	5.46
1989	4	16	25.	30.3	9.6	0.00	0.24	5.72
1989	4	17	24.	20.8	11.5	0.00	0.37	6.24
1989	4	18	26.	22.5	8.0	0.00	0.48	7.28
1989	4	19	25.	26.0	5.2	0.00	0.52	4.94
1989	4	20	24.	32.4	11.6	0.00	0.49	6.89
1989	4	21	25.	33.2	13.1	0.00	0.44	6.63
1989	4	22	20.	34.5	14.3	0.00	0.28	5.59
1989	4	23	23.	33.6	12.9	0.00	0.23	6.50
1989	4	24	19.	32.3	14.5	0.00	0.33	6.89
1989	4	25	24.	31.2	9.6	0.00	0.31	6.76
1989	4	26	27.	31.5	5.9	0.00	0.19	6.76
1989	4	27	28.	24.3	6.1	0.00	0.20	7.67
1989	4	28	28.	24.0	5.3	0.00	0.32	5.46
1989	4	29	28.	17.5	4.6	0.00	0.48	8.06
1989	4	30	20.	20.2	3.7	1.02	0.55	6.11
1989	5	1	24.	16.2	3.0	0.00	0.68	6.11
1989	5	2	22.	25.0	7.6	0.00	0.48	7.02
1989	5	3	14.	20.2	7.9	1.27	0.80	5.85
1989	5	4	21.	25.4	5.4	5.08	0.75	5.98
1989	5	5	29.	23.9	4.5	0.00	0.51	3.77
1989	5	6	22.	24.0	8.2	0.00	0.49	5.59
1989	5	7	29.	31.7	10.4	0.00	0.52	5.07
1989	5	8	27.	32.7	12.4	0.00	0.39	5.59
1989	5	9	26.	22.4	13.9	0.00	0.48	8.84
1989	5	10	25.	22.3	10.8	0.00	0.44	6.76
1989	5	11	9.	17.4	10.1	0.00	0.80	9.36
1989	5	12	20.	17.2	9.4	12.70	0.87	7.80
1989	5	13	28.	23.6	10.8	0.00	0.66	5.20
1989	5	14	18.	21.1	10.9	0.00	0.80	6.63
1989	5	15	13.	21.1	11.6	0.25	0.82	6.37
1989	5	16	8.	20.0	11.5	53.09	0.94	8.58
1989	5	17	15.	18.2	7.6	21.34	0.90	6.89
1989	5	18	28.	24.3	9.0	2.29	0.70	6.89
1989	5	19	30.	30.8	11.9	0.00	0.52	5.46
1989	5	20	24.	26.0	16.0	0.00	0.76	5.98
1989	5	21	19.	32.7	16.2	0.00	0.53	7.67
1989	5	22	30.	29.3	14.9	0.00	0.62	6.37

Electronic database continues....

Table G-5. Daily Climate Data, Formatted for EPIC -- Bushland, Texas, 1995-1997 alfalfa, data from weather pen at lysimeter site

Year	Mon	Day	Rad MJ/m^2	Tmax C	Tmin C	Prcp mm	Rhum frac	10 m Wind m/s
1995	9	13	25.	30.3	13.2	0.00	0.52	3.05
1995	9	14	16.	27.5	13.5	0.00	0.59	3.60
1995	9	15	5.	18.1	15.8	9.40	0.93	2.50
1995	9	16	22.	28.9	15.6	0.00	0.73	2.37
1995	9	17	12.	25.6	17.7	2.90	0.85	4.37
1995	9	18	17.	27.7	16.6	27.10	0.83	6.07
1995	9	19	10.	18.6	12.1	0.00	0.84	6.03
1995	9	20	17.	22.9	10.6	0.00	0.84	6.41
1995	9	21	3.	15.8	1.6	9.30	0.94	9.39
1995	9	22	17.	12.5	2.9	0.00	0.71	5.03
1995	9	23	23.	25.1	4.0	0.00	0.72	6.70
1995	9	24	8.	14.1	8.8	5.30	0.89	4.99
1995	9	25	18.	19.7	8.0	5.30	0.81	3.04
1995	9	26	15.	24.0	10.5	0.00	0.83	5.71
1995	9	27	22.	31.2	11.9	0.00	0.63	3.74
1995	9	28	19.	32.3	12.1	0.00	0.58	6.10
1995	9	29	22.	28.3	14.0	0.00	0.64	7.31
1995	9	30	22.	21.9	12.3	0.00	0.56	5.17
1995	10	1	22.	23.8	5.6	0.00	0.61	4.82
1995	10	2	16.	18.5	9.2	21.90	0.83	4.24
1995	10	3	16.	20.9	7.6	0.00	0.76	4.38
1995	10	4	22.	29.3	9.4	0.00	0.55	8.84
1995	10	5	22.	19.5	5.3	0.00	0.47	5.92
1995	10	6	21.	17.7	3.6	0.00	0.51	4.52
1995	10	7	21.	24.2	2.5	0.00	0.59	6.92
1995	10	8	21.	26.7	9.5	0.00	0.47	5.42
1995	10	9	20.	25.4	6.6	0.00	0.62	2.69
1995	10	10	20.	22.2	8.4	0.00	0.72	4.50
1995	10	11	20.	27.6	9.9	0.00	0.62	2.82
1995	10	12	20.	28.7	8.5	0.00	0.44	7.25
1995	10	13	19.	16.3	3.3	0.00	0.40	7.72
1995	10	14	20.	22.1	2.1	0.00	0.45	3.51
1995	10	15	20.	28.1	3.9	0.00	0.46	2.51
1995	10	16	18.	27.8	6.6	0.00	0.43	5.98
1995	10	17	18.	26.8	8.7	0.00	0.36	4.88

Electronic database continues….

Table G-6. Complete Alfalfa Irrigation Data, Bushland, Texas

Year	Month	Day	Irrigation (mm)
1995	Sep	14	11.0
1995	Oct	17	14.2
1995	Oct	20	14.8
1995	Oct	26	14.0
1995	Nov	13	14.2
1995	Nov	20	12.3
1995	Nov	30	13.0
1995	Dec	14	13.8
1996	Feb	22	13.0
1996	Feb	26	15.0
1996	Mar	11	17.7
1996	Mar	14	17.2
1996	Mar	22	18.7
1996	Apr	2	22.3
1996	Apr	8	17.2
1996	Apr	10	17.3
1996	Apr	12	15.2
1996	Apr	15	24.7
1996	Apr	17	22.6
1996	Apr	19	17.2
1996	Apr	22	24.4
1996	Apr	24	26.3
1996	Apr	26	13.9
1996	Apr	29	26.5
1996	May	1	25.2
1996	May	3	16.2
1996	May	6	28.2
1996	May	8	35.5
1996	May	9	26.6
1996	May	13	24.6
1996	May	15	23.1
1996	May	29	37.7
1996	May	31	15.5
1996	Jun	3	25.5
1996	Jun	5	24.7
1996	Jun	7	18.4
1996	Jun	12	21.7
1996	Jun	14	16.4
1996	Jun	17	28.3
1996	Jun	19	25.5
1996	Jun	21	25.7
1996	Jun	24	17.6
1996	Jul	19	16.6
1996	Jul	22	20.7
1996	Jul	29	26.6
1996	Aug	2	19.3
1996	Aug	5	27.5
1996	Aug	7	26.4
1996	Aug	22	19.1
1996	Aug	23	19.8.
1996	Sep	4	44.4
1996	Sep	23	19.5
1996	Sep	30	15.3
1996	Oct	16	16.4
1996	Oct	24	39.5
1996	Nov	20	35.5
1997	Mar	13	13.6
1997	Mar	19	24.1
1997	Mar	25	22.8
1997	Mar	31	24.7
1997	Apr	7	12.1
1997	Apr	17	26.0
1997	Apr	21	25.5
1997	May	8	26.4
1997	May	12	17.1
1997	May	16	18.3
1997	May	20	19.4
1997	May	23	21.7
1997	May	27	25.1
1997	Jun	25	35.8
1997	Jun	27	16.8
1997	Jun	30	25.6
1997	Jul	2	25.5
1997	Jul	5	25.0
1997	Jul	7	16.9
1997	Jul	9	16.5
1997	Jul	10	13.7
1997	Jul	14	28.0
1997	Jul	16	13.1
1997	Jul	17	27.5
1997	Jul	28	31.3
1997	Jul	30	28.2
1997	Aug	2	29.5
1997	Aug	4	25.8
1997	Aug	18	20.7
1997	Aug	20	16.6
1997	Aug	30	33.1
1997	Sep	1	16.3
1997	Sep	3	39.3
1997	Sep	8	17.3
1997	Sep	10	23.4
1997	Sep	12	16.2
1997	Sep	15	15.5
1997	Sep	16	18.9
1997	Sep	18	14.9
1997	Oct	7	33.4

Table G-7. Complete Corn Irrigation Data, Bushland, Texas

Year	Month	Day	Irrigation (mm)
1989	Apr	27	22.8
1989	Apr	28	13.3
1989	May	6	11.7
1989	May	23	12
1989	Jun	27	17.4
1989	Jul	5	23.2
1989	Jul	7	29.1
1989	Jul	11	27.3
1989	Jul	18	25.7
1989	Jul	21	21.8
1989	Jul	25	14.7
1989	Aug	1	10.4
1989	Aug	4	20.1
1989	Aug	18	19.2
1989	Sep	5	13.7
1990	May	10	15.4
1990	May	11	20.5
1990	May	24	19.6
1990	Jun	8	21.7
1990	Jun	13	22.7
1990	Jun	20	19.4
1990	Jun	22	23.5

Year	Month	Day	Irrigation (mm)
1990	Jun	25	24.3
1990	Jun	27	21.7
1990	Jun	29	20.8
1990	Jul	2	11.0
1990	Jul	3	15.1
1990	Jul	5	12.9
1990	Jul	6	17.7
1990	Jul	9	19.2
1990	Jul	10	17.8
1990	Jul	12	24.5
1990	Jul	13	12.5
1990	Jul	17	24.2
1990	Jul	31	20.5
1990	Aug	2	17.5
1990	Aug	6	21.0
1990	Aug	9	18.0
1990	Aug	24	14.8
1990	Aug	28	20.9
1990	Aug	30	43.9
1990	Sep	4	17.1
1990	Sep	7	18.7
1990	Sep	10	20.0

Table G-8. Operations data, Alfalfa (1995-1998), Bushland, Texas

Pesticide and herbicide applications were not included in the operations table.

Year	Day of year	Calendar date	Operation	Other notes
1995	256	Sep 13	Plant alfalfa	24 lb/acre
1996	142	May 21	Harvest	
	190	Jul 8	Harvest	
	228	Aug 15	Harvest	
	281	Oct 7	Harvest	
1997	084	Mar 25	Fertilize	237 g 11-52-0
	168	Jun 17	Harvest	
	203	Jul 22	Harvest	
	237	Aug 25	Harvest	
	273	Sep 30	Harvest	
	302	Oct 29	Fertilize	388 g 11-52-0

Table G-9. Operations data, Corn (1989-1990), Bushland, Texas

Year	Day of year	Calendar Date	Operation	Other notes
1989	19	Jan 19	Fertilize	140 lb/acre N fertilizer
	75	Mar 16	Tilled	Shovel work
	75	Mar 16	Bedded	
	116	Apr 26	Planted lys.	7” spacing, by hand
	122	May 2	Reseeded	Damage by mice
	151	May 31	Cultivated	
	164	Jun 13	Cultivated	
	167	Jun 16	Thinned plants	To 10” spacing
	172	Jun21	Cultivated	
	297	Oct 24	Harvest lys.	Hand harvest
	304	Oct 31	Harvested	Broke over plants to match field
1990	3	Jan 3	Cultivated	Moldboard simulation
	113	Apr 23	Cultivate	Rototilled fertilize 140 lb/acre N
	129	May 9	Planted	7” to 8” spacing, 6 plants/m^2
	150	May 30	Cultivated	
	163	Jun 12	Cultivated	
	169	Jun 18	Cultivated	
	302	Oct 29	Harvest	

Appendix H

Measured data from Coshocton, Ohio

The following tables contain measured data from Coshocton, Ohio that were available for use in model evaluation.

Ten-layer description of the soil in the lysimeter and surrounding watershed derived from soil descriptions by Kelly et al., (1975), Harold and Dreibelbis, (1958), and Harrold and Dreibelbis (1967). Information contained in the Soils-5 Database, (1993) was used for reference, but not for primary description. There was some variability in soil descriptions, possibly resulting from location of soil profile examined. The values shown generally follow the description of Kelly et al., (1975) who performed a soils classification. The soil was classified in the *Dekalb* series.

Table H-1a. Properties of the soil in lysimeter Y101d and surrounding watershed, Coshocton, Ohio

Depth to bottom of layer, m	**0.01**	**0.10**	**0.20**	**0.30**	**0.41**	**0.60**	**0.84**	**1.05**	**1.30**	**2.44**
Bulk density, Mg/m^3	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.5	1.5	1.8
Wilting point, v/v	0.08	0.08	0.08	0.08	0.10	0.07	0.10	0.10	0.10	0.07
Field capacity, v/v	0.31	0.31	0.28	0.27	0.27	0.27	0.27	0.24	0.20	0.18
Sand, %	30	30	30	27	48	48	45	71	71	76
Silt, %	52	52	52	52	37	37	36	16	16	13
pH	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	5.0
Organic carbon, % (O.M./1.72)[a]	1.8	1.8	1.8	0.35	0.35	0.35	0.11	0.08	0.08	0.04
CACO**3, %										
C. E.C[b], cmol/kg	11	11	11	7.6	7.1	7.1	7.1	7.1	7.1	1.9
Coarse fragments (rock>2 mm)%	10	10	10	10	10	40	40	40	40	rock[c]

[a] O.M. = Organic matter

[b] C.E.C. = Cation exchange capacity

[c] Sandstone rock

Kelly, G. E., W. M. Edwards, L. L. Harold and J. L. McGuinness. 1975. *Soils of the North Appalachian Experimental Watershed*. USDA, Washington, D. C., Misc. Pub. 1296

Harrold, L. L., and F. R. Dreibelbis. 1958. *Evaluation of agricultural hydrology by monolith lysimeters, 1944-55.* USDA, Tech. Bul. 1179, 166 pp.

Harrold, L. L. and F. R. Dreibelbvis. 1967. *Evaluation of agricultural hydrology by monolith lysimeters, 1956-62.*USDA, Tech. Bul. 1367, 123 pp.

SCS Soils-5, 1993. *Database* USDA from EarthInfo, Inc., 5541 Central Avenue, Boulder, CO 80301

Table H-1b. Descriptions of the soil in lysimeter Y101d and surrounding watershed, Coshocton, Ohio

Kelly et al., (1975) described the Dekalb silt loam soil as follows:

Depth m	**Rock %>2mm**	**Description**
0.076	10	Very dark, grayish-brown, dark brown crushed silt loam; weak, fine, subangular, blocky structure; parting to weak, fine, granular structure; friable; many roots; 10% sandstone fragments
0.178	10	Dark, yellowish-brown, crushed silt loam (other properties similar to 0-.076 m layer)
0.406	10	Silt loam; weak, medium, subangular, blocky, structure; friable; common roots; 10% sandstone fragments.
0.635	40	Channery loam *(note: contains flat pieces of sandstone)* weak, medium, subangular, blocky structure; friable; common roots; clay films; 40% sandstone fragments.
0.711	n/a	Soft sandstone with dark brown clay films

Harrold and Dreibelbis (1958) described the soil at Y101d as follows:

Depth m	Description
0.203	Dark brown silt loam with texture approaching a loam
0.406	Brown to yellowish-brown silt loam to loam with some sandstone fragments
0.838	Brown to yellowish-brown loam with sandstone fragments
1.295	Decomposed sandstone with sandstone fragments
2.438	Slightly decomposed sandstone rock with few sandstone fragments

Table H-2. Model testing data – Coshocton, Ohio

Parameter	Meadow	
Years	1970 – 79 and 1987 - 93	
Elevation, m (feet)	361 (1184)	
Latitude (deg.)	40.4^{o} N	
lysimeter type	Weighing and Recording	
soil	Undisturbed soil monolith	
dimensions *l* x *w* x *d* (m)	4.267 x 1.896 x 2.438	
surface area m^2 (ha)	8.09 (.00081)	
surface slope (%)	23.2	
bottom suction	No suction - natural gravity flow through 1.1 m parent rock.	
precision	0.25 mm (weight calibration)	
Soil type	Dekalb silt loam	
Wet soil albedo	0.15 (estimated)	
Field capacity[1], mm	540mm	
Wilting point[1], mm	198 mm	
Available water capacity[1,2] (mm)	342 mm	
Initial soil-water content (mm)	Jan. 1 70, lys. measurement = 482.5 mm, [EPIC use 482.5/540 = 0.89]	
Soil hydrologic group	Soil surveyor classification B -- **Use A** - the site soil is "highly permeable"	
Crop	Meadow	
1970 – 1979	Alfalfa	Orchardgrass
Plant type	Perennial legume	Perennial grass
Plant population (plants/m^2) Estimated actual survival in mixture	50 in mix	150 in mix
Max leaf-area-index (other source)	5	5
Max crop height (m) (other source)	1.25	1.2
Max root depth (m) [limited by rock]	1.3	1.3
irrigated	No	
Soil pH control	Agricultural lime applied to create neutral pH	

[1] Field capacity & wilting point, from Tech. Bul. 1367
[2] Available water content = field capacity – wilting point

Table H-3. Average monthly climate data – Coshocton, Ohio

The long-term averages in this table were calculated from the 37-year record of measured data at NAEW headquarters, Coshocton, Ohio except for radiation, humidity, and wind. Appendix G contains a description of the derivation of numbers in this table and explains the reason and method for estimating solar radiation.

Parameter	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YR
Maximum Temperature, C	0.43	2.00	8.02	14.92	20.79	25.35	27.53	26.82	23.29	16.85	9.87	2.87	14.90
Minimum Temperature, C	-8.31	-7.14	-2.02	4.25	10.08	14.63	17.09	16.32	12.71	6.08	0.16	-5.24	4.88
St. Dev. Max. Temperature	6.84	6.86	7.40	6.86	5.45	4.02	3.24	3.29	4.71	5.70	6.43	6.67	
St. Dev. Min. Temperature	6.80	6.53	5.89	5.42	4.78	3.71	2.93	3.07	4.48	4.84	6.96	6.33	
Precipitation, mm	55.9	51.6	76.7	84.7	92.6	100.9	12.2	81.0	74.3	57.4	75.5	64.0	826.8
St. Dev. Precipitation	6.77	7.35	8.30	9.01	9.46	13.95	13.92	11.62	12.03	8.03	8.51	6.84	
Skew Factor, Precipitation	2.29	2.91	3.59	2.37	2.37	3.12	2.60	1.98	3.46	2.52	2.46	2.14	
Probability wet day after dry	0.29	0.29	0.34	0.32	0.29	0.26	0.28	0.23	0.22	0.23	0.29	0.29	
Probability wet day after wet	0.41	0.40	0.44	0.48	0.48	0.44	0.36	0.36	0.38	0.37	0.43	0.48	
Days Precipitation	10.24	9.16	11.65	11.27	11.03	9.46	9.35	8.19	7.97	8.16	10.19	11.00	
Solar Radiation, MJ/m*2	6.72	9.29	12.67	14.65	20.26	23.53	22.87	20.49	14.59	11.43	7.61	6.38	14.21
Relative humidity	0.90	0.81	0.57	0.61	0.62	0.62	0.66	0.68	0.66	0.68	0.64	0.73	0.68
Wind, m/s	5.21	5.11	5.29	5.07	4.29	3.85	3.42	3.22	3.53	3.94	4.97	5.02	4.41

Table H-4. Daily Climate Data, formatted for EPIC – Coshocton, Ohio, 1970 – 79, lysimeter Y101d, precipitation measured by lysimeter

Year	Mon	Day	Rad MJ/m^2	Tmax C	Tmin C	Prcp mm	Rhum frac	10m Wind m/s
1970	1	1	0.	-1.7	-3.9	3.48	0.	0.
1970	1	2	0.	-2.2	-5.0	3.43	0.	0.
1970	1	3	0.	-2.2	-12.2	0.89	0.	0.
1970	1	4	0.	-7.2	-10.6	3.81	0.	0.
1970	1	5	0.	0.0	-9.4	0.61	0.	0.
1970	1	6	0.	-2.8	-10.0	1.07	0.	0.
1970	1	7	0.	-10.0	-20.0	2.64	0.	0.
1970	1	8	0.	-19.4	-22.2	9.02	0.	0.
1970	1	9	0.	-16.1	-21.7	3.66	0.	0.
1970	1	10	0.	-10.6	-16.7	0.97	0.	0.
1970	1	11	0.	-6.7	-16.7	3.25	0.	0.
1970	1	12	0.	-3.9	-8.3	1.35	0.	0.
1970	1	13	0.	-4.4	-13.9	1.57	0.	0.
1970	1	14	0.	-5.0	-11.1	1.52	0.	0.
1970	1	15	0.	-1.1	-12.2	2.13	0.	0.
1970	1	16	0.	6.1	-4.4	0.05	0.	0.
1970	1	17	0.	3.9	1.7	1.80	0.	0.
1970	1	18	0.	1.7	-12.2	4.83	0.	0.
1970	1	19	0.	-6.7	-12.8	3.20	0.	0.
1970	1	20	0.	-10.6	-13.9	4.70	0.	0.
1970	1	21	0.	-13.3	-20.0	3.10	0.	0.
1970	1	22	0.	-11.7	-21.1	4.04	0.	0.
1970	1	23	0.	-6.7	-12.2	2.95	0.	0.
1970	1	24	0.	-3.9	-17.2	3.33	0.	0.
1970	1	25	0.	5.0	-4.4	1.80	0.	0.
1970	1	26	0.	0.0	-2.8	1.70	0.	0.
1970	1	27	0.	0.0	-1.7	2.92	0.	0.
1970	1	28	0.	13.3	-3.3	0.00	0.	0.
1970	1	29	0.	13.3	-1.1	26.19	0.	0.
1970	1	30	0.	-1.1	-7.2	0.00	0.	0.
1970	1	31	0.	4.4	-6.1	0.00	0.	0.
1970	2	1	0.	7.8	2.2	0.00	0.	0.
1970	2	2	0.	7.8	-4.4	22.02	0.	0.
1970	2	3	0.	-4.4	-17.8	4.06	0.	0.
1970	2	4	0.	-6.1	-21.1	0.00	0.	0.
1970	2	5	0.	0.6	-6.1	0.00	0.	0.
1970	2	6	0.	0.6	-3.9	0.00	0.	0.
1970	2	7	0.	4.4	-6.7	4.24	0.	0.
1970	2	8	0.	4.4	0.6	4.47	0.	0.
1970	2	9	0.	4.4	0.6	6.73	0.	0.
1970	2	10	0.	0.6	-3.3	0.00	0.	0.
1970	2	11	0.	-0.6	-3.9	0.00	0.	0.
1970	2	12	0.	-3.3	-9.4	1.35	0.	0.
1970	2	13	0.	-6.7	-10.6	0.30	0.	0.
1970	2	14	0.	-5.6	-12.2	0.00	0.	0.

Electronic database continues….

Table H-5. Daily Climate Data, formatted for EPIC – Coshocton, Ohio, 1987-93, lysimeter Y101d, precipitation measured by lysimeter

Year	Mon	Day	Rad MJ/m^2	Tmax C	Tmin C	Prcp mm	Rhum frac	10m Wind m/s
1987	1	1	1.8	2.8	-2.2	8.18	0.99	2.52
87	1	2	0.4	0.0	-1.7	5.94	0.84	9.19
87	1	3	0.9	1.2	-2.2	0.00	0.88	7.44
87	1	4	4.7	0.6	-5.6	0.00	0.93	7.29
87	1	5	12.4	1.7	-8.9	0.00	0.87	5.89
87	1	6	6.9	7.8	-6.1	0.00	0.93	6.98
87	1	7	1.4	7.2	0.0	0.00	0.90	8.90
87	1	8	1.5	0.0	-1.7	0.00	0.92	4.86
87	1	9	2.1	-0.6	-3.3	2.01	0.99	9.42
87	1	10	1.6	2.8	-2.2	3.15	0.91	7.87
87	1	11	2.3	-1.1	-2.2	1.19	0.99	1.62
87	1	12	2.9	-0.6	-3.3	0.00	0.91	4.24
87	1	13	9.8	6.1	-4.4	0.00	0.97	2.36
87	1	14	3.7	8.9	1.7	0.61	0.84	6.13
87	1	15	0.6	8.3	-0.6	0.86	0.99	5.96
87	1	16	6.3	0.0	-5.0	0.00	0.71	4.10
87	1	17	8.5	2.2	-7.2	0.00	0.99	8.46
87	1	18	0.9	3.9	-1.7	2.67	0.99	4.84
87	1	19	1.2	3.9	-3.9	16.87	0.99	5.40
87	1	20	4.8	-1.1	-4.4	0.00	0.79	0.92
87	1	21	12.0	0.0	-10.0	0.00	0.78	10.17
87	1	22	2.6	-0.6	-5.0	0.66	0.87	9.29
87	1	23	7.1	-3.3	-17.9	2.54	0.99	8.42
87	1	24	12.1	-11.1	-20.0	0.00	0.88	3.81
87	1	25	12.2	-8.3	-16.1	0.00	0.59	4.84
87	1	26	9.3	-5.0	-13.3	0.00	0.66	2.60
87	1	27	8.8	-3.9	-14.4	0.00	0.96	4.94
87	1	28	3.2	-3.3	-8.3	0.28	0.99	3.18
87	1	29	4.7	0.0	-5.6	11.58	0.99	5.10
87	1	30	0.8	2.8	-2.2	5.38	0.93	2.88
87	1	31	5.9	0.6	-3.3	0.00	0.95	6.85
87	2	1	4.0	5.0	-3.9	0.28	0.85	3.76
87	2	2	9.0	8.3	2.2	0.00	0.64	5.39
87	2	3	2.1	5.0	0.6	0.00	0.65	5.52
87	2	4	8.9	3.3	-2.2	0.00	0.90	10.96
87	2	5	13.3	6.1	-6.1	0.00	0.73	4.32
87	2	6	12.2	9.4	-2.2	0.00	0.85	4.44
87	2	7	11.8	8.3	-2.2	0.00	0.64	6.97
87	2	8	2.5	5.0	-9.4	1.14	0.95	2.34
87	2	9	12.9	-1.7	-9.4	0.28	0.79	10.48
87	2	10	12.4	5.0	-7.2	0.00	0.78	3.08
87	2	11	12.0	9.4	-3.9	0.00	0.70	0.53
87	2	12	4.3	5.0	0.6	4.88	0.99	5.55
87	2	13	13.0	2.8	-6.1	0.00	0.82	8.23
87	2	14	2.7	1.7	-6.1	0.00	0.79	7.14

Electronic database continues….

Table H-6a. Coshocton, Ohio, Operations Summary: 1970 through 1979, lysimeter Y101d

Year	Operation and/or description
1970	alfalfa/orchardgrass "improved practice", 8 lb/acre tordon, 330 lb/acre KCL
1971	alfalfa/orchardgrass 1 t/a lime (Apr 16); 1000 lb/acre 16-16-16 (Apr 21)
1972	alfalfa/orchardgrass 1000 lb/acre 16-16-16 (June 2)
1973	alfalfa/orchardgrass 1000 lb/acre 16-16-16
1974	alfalfa/orchardgrass 1000 lb/acre 16-16-16 (May 1); 1.5 t/a manure (July 17)
1975	orchardgrass "improved practice"
1976	orchardgrass/alfalfa 150 lb/acre NH4NO3 (March 24)
1977	orchardgrass 150 lb/acre NH4NO3 (Apr 4)
1978	orchardgrass 50 lb N/A as NH4NO3 (Apr 17)
1979	orchardgrass 50 lb N/A as methylene urea (Mar 22, June 13, Aug16)

For model evaluation use:

Fertilizer: 15-15-15 at 1070 lb/acre
1970-74, cover is 50% alfalfa, 50% orchardgrass
1975-79, cover is 10% alfalfa, 90% orchardgrass

Harvest dates varied slightly according to season from year-to-year, for model evaluation use: May 25, July 7, and Aug. 23

Table H-6b. Coshocton, Ohio, Operations Summary: 1987 through 1993, lysimeter Y101d

Year	Operation and/or description
1987-93	50 percent Orchardgrass and 50 percent Bromegrass, “improved pasture”
1987	50 lb/acre N on Apr. 3, June 5, and Aug. 5
1988	50 lb/acre N on Apr. 13, June 22, and Aug. 2
1989	50 lb/acre N on Apr. 28, June 5, and Aug. 1, 69 lb/acre P on Sept. 1
1990	120 lb/acre K on Aug. 22
1991	120 lb/acre K on Aug. 13, 58 lb/acre P on Aug. 21
1992	Record not available
1993	Record not available

For model evaluation use:

Fertilizer: 56 Kg/ha N on Apr. 16, June 26, and July 7
50 Kg/ha P one-time/ year
77 Kg/ha K one-time/ year

Harvest dates varied slightly according to season from year-to-year, for model evaluation use: May 25, July 7, and Aug. 23

Appendix I

Climate Data and Statistics for Lysimeter Y101d, Coshocton, Ohio North Appalachian Experimental Watershed (NAEW)

Model evaluation requires use of the best available climate input data in order to assess the accuracy of estimated water balance parameters that are important to evapotranspiration (ET) landfill cover design. Mitretek collected climate data for lysimeter Y101d at the North Appalachian Experimental Watershed (NAEW), Coshocton, Ohio and estimated statistics required by the models from the best available sources. Two sets of lysimeter and climate data were available, 1970-79 and 1987-93. This report describes the daily data available, estimates of statistics required by models, problems encountered and how the climate data were used in model evaluation.

Daily climate generation models

WXgen (WXgen, 1999) and WXparm (WXparm, 1999) are daily climate generating and climate parameter estimating models respectively. Each of them runs independently, but will read files generated by the other. In addition, the EPIC model (Sharpley and Williams, 1990a) uses these programs internally and produces climate data identical to that generated by WXgen. The climate generators WXgen, and WXparm along with those in the EPIC model were previously shown to provide accurate and reliable estimates of daily climate parameters (Sharpley and Williams, 1990a & 1990b and Williams et al., 1990). WXgen and WXparm are useful tools with which to estimate climate parameters or to replace missing data in weather files.

Because WXgen and WXparm are available as stand-alone models, generated data are available to the user of any model. Monthly input statistics are required by models that generate daily weather data.

Model generated climate data is not equivalent to good measurements for the site. Therefore, measured, daily data of adequate quality were used in preference to generated data in all instances where it was available.

Description of data

Daily climate records were included in the data sets obtained from the NAEW, Coshocton, Ohio, for lysimeter Y101D, for the 1970-79 and 1987-93 time periods, except as noted below. The data were recorded in English units and converted to metric units by Mitretek. The climate data used in model evaluation are described below:

Precipitation

Because precipitation measurements were available from two differing methods of measurement, it was necessary to evaluate the data to select which to use for model evaluation. NAEW recorded precipitation measurements in two data sets for the period 1970-79, (climatic.y70 – Y79 and lysim101.Y70 – Y79). The "climatic" data set contains precipitation measurements derived from a standard, class-A rain gauge at station headquarters. The "Lysim101" data set contained daily precipitation measured by a class-A rain gauge located near the lysimeter in addition to estimates of daily precipitation from the weighing and recording lysimeter records.

Standard rainfall measurement: The following "standard" is generally accepted for hydrologic estimates and research. A standard rain gauge includes a collection tube with a sharp-edged, circular orifice at the top to catch precipitation. The U.S. Weather Bureau standardized the size of the orifice at eight inches (203 mm) (Chow, 1964; Brakensiek et al., 1979; and Schwab et al., 1966). The height of measurement is not as closely defined; however, it is normally taken to be either 30 or 40 inches (762–1,016 mm) above ground surface. Measurements for hydrologic research are normally standardized at 30 inches (762 mm) above ground surface (Brakensiek et al., 1979) and utilize an eight-inch orifice; that gauge is described herein as a "class-A" or "standard" gauge.

Factors affecting accuracy**:** Wind is the greatest single cause of error in precipitation measurements for standard gauges. Schwab et al., (1966) report that winds of 10 mph caused a rainfall catch deficit of 17 percent, but a wind of 30 mph caused a deficit of 60 percent. Brakensiek et al., (1979) state, "An ideal [gauge] exposure would eliminate all turbulence and eddy currents near the gauge." They state that wind may cause a –5 to –80 percent error in precipitation measurement and that errors resulting from other causes were between +1.0 and –1.5 percent.

Gauge height above the ground surface is important because wind movement strongly affects the gauge catch, and wind velocity is a logarithmic function of height above ground surface. Although the true measurement of rainfall has not been defined, rainfall measurements at ground level are commonly accepted as most accurate. For example, "pit gauges" are placed in a hole so that their top is at ground level; they may catch up to 15 percent more rainfall than gauges with their tops mounted at standard height (Neff, 1977).

The results of research on the effect of gauge height are variable. Allis et al., (1963) reported that a gauge mounted six feet above ground surface captured the same amount of rainfall as a standard gauge at 30 inches; however, the gauge at standard height captured 30 percent more snow.

Snow is difficult to measure accurately because it is so easily moved by wind and the resulting eddy currents around a standard gauge. Lysimeters catch precipitation at ground level; therefore they minimize the effect of wind. In addition they measure precipitation for a large surface area. McGuinness (1966) found that lysimeters measured six percent more rainfall than a standard gauge, but 27 percent more snowfall.

There are substantial differences between the precipitation amount measured by the standard rain gauge located near lysimeter Y101d and that derived from the lysimeter measurements. Figure I-1 shows the average monthly precipitation measure by the standard gauge and that measured by lysimeter Y101d at Coshocton Ohio. Lysimeter Y101d measured 10.5 percent more total precipitation than the nearby standard gauge during 1987 - 93. The difference was greater during cold months when most precipitation fell as snow than during warm months when precipitation was predominantly rain.

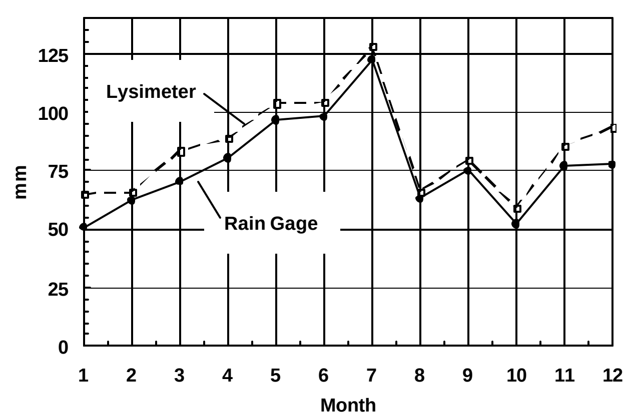

Figure I-1 Average monthly precipitation for 1987-93 at lysimeter Y101d.

Model estimates are usually based on rain gauge data, because lysimeter measurements are almost never available. Even though they are assumed to be accurate, the error of rain gauge catch is unknown for most sites. The purpose of this work is to evaluate models. Therefore, Mitretek used lysimeter measured precipitation because it appeared to be the best available measurement.

Air temperature

The models required either average daily or daily maximum and minimum air temperatures. Model developers defined the “average” daily temperature as the mean of the maximum and minimum value for the day.

The climatic data sets described above for 1970-79 and for 1987-93, contained daily maximum and minimum temperatures. Mitretek estimated missing temperature measurements for four days in the 1987-93 temperature records with the model WXgen (WXgen, 1999).

Solar radiation

Solar radiation was measured at the NAEW headquarters at a distance less than ¼ mile from lysimeter Y101d. It was recorded as total daily summation of radiation for 1970-79 and for 1987-93 as daily summation until November 1989 and as hourly summations thereafter. Measurement of solar radiation at hydrologic experimental stations was a relatively new practice during 1970-79.

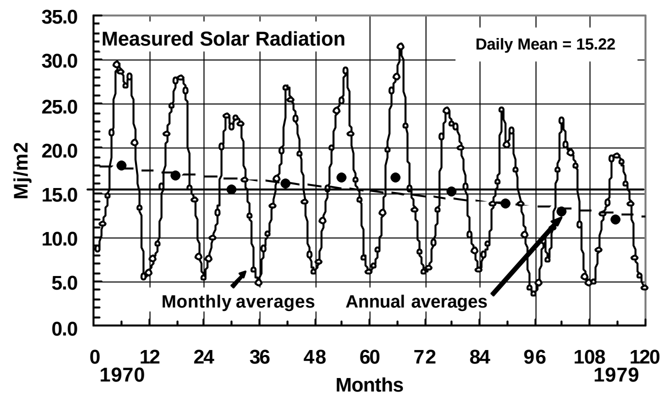

Figure I-2. Monthly and annual average solar radiation during 1970 through 1979.

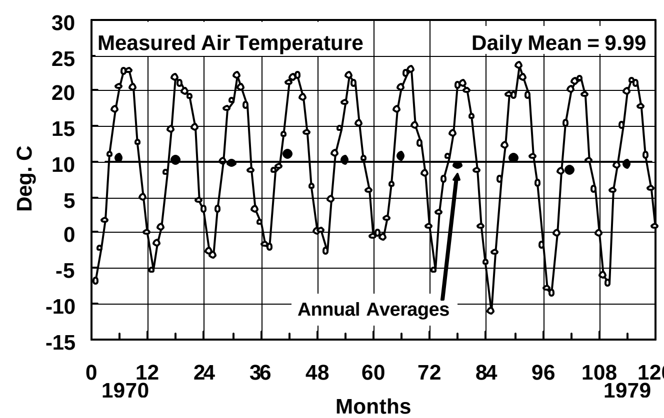

Figure I-3. Monthly and annual average air temperature during 1970 to 1979.

Whereas we found no problems with the precipitation or temperature data, there is a downward trend in the annual total solar radiation measured for lysimeter Y101d during the 10-year period from 1970 to 1979, Figure I-2. Annual, average solar radiation should be relatively constant from year-to-year. Reduced solar radiation should result in reduced monthly and annual air temperature; however, air temperature measurements at lysimeter Y101d demonstrate that air temperature remained constant during the 10-year period, Figure I-3. Estimates of ET by methods that used the measured daily solar radiation values differed from the lysimeter measured values; but temperature based estimates of ET were similar. In addition, when Mitretek entered average, monthly solar radiation measurements for the station at New Philadelphia, Ohio into the EPIC model and allowed EPIC to estimate daily, solar radiation values, the resulting estimates of ET corresponded well with the measured values.

Because the measured solar radiation data appear to be in error during 1970-79, Mitretek developed an alternate way to obtain these important daily values for model input. The EPIC model and WXgen and WXparm were previously shown to provide accurate and reliable estimates of daily solar radiation from known values of monthly radiation (Sharpley and Williams, 1990a & 1990b and Williams et al., 1990). Therefore, Mitretek used the mean monthly values of solar radiation from the nearest available records at New Philadelphia, Ohio, located about 42 km (26 miles) from the site as input to the WXparm model. The estimates by WXparm of daily values for the years 1970 through 1979 were used for model evaluation.

The measured values of solar radiation show no evidence of a trend for the period 1987-93, Figure I-4. In addition, the daily mean value is near that for nearby climate stations. Therefore, Mitretek used the measured daily values of solar radiation for model estimates of ET during the period 1987-93. There were 48 missing values among the 2,557 daily measurements; they were estimated.

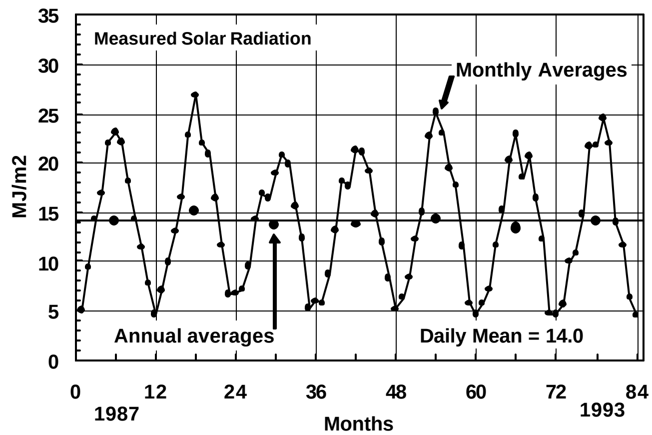

Figure I-4. Monthly and annual average solar radiation during 1987 to 1993.

The radiation measurements from January 1, 1987 through November 8, 1989 are daily measurements, but those from November 9, 1989 through December 31, 1993 are hourly values. The hourly data contained radiation measurements during nighttime hours when there should be no measurable radiation. Most hourly nighttime measurements were one langley. Dr. Robert Malone of NAEW (personal communication) stated that night lighting for the station headquarters was located near the sensor, and was the probable cause of the anomalous readings. The nighttime values increased each days total so Mitretek changed the radiation for nighttime hours to zero. Mitretek estimated nighttime hours from a table of Civil Twilight published on the U.S. Naval Observatory website.

Relative humidity

Daily humidity measurements were missing from the NAEW data sets during 1970 – 1979. Therefore, daily relative humidity was estimated for 1970-79 by WXgen from mean values derived from the 37-year record for the NAEW contained in the National Climatic Data Center files (NCDC, 2001). The relative humidity measurements provided in the 1987-93 files are incomplete, so Mitretek used the WXgen model to estimate missing daily values.

Wind

Daily measured wind speed was available in both the 1970-79 and 1987-93 NAEW data sets. For model evaluations, wind should be measured at a height of 10 m. Wind speeds recorded in the NAEW data are less than half those recorded at two nearby climate stations. The height of measurement for the NAEW wind data was stated to be 10 m; however, later correspondence indicated that the height may have been near 2 feet. The correct height at which the wind speed was measured is therefore, in doubt. Wind speed may be substantially reduced by obstacles (trees or buildings) near the wind gauge and is substantially affected by height of measurement. Mitretek used average, monthly wind speed from New Philadelphia, Ohio, 42 km (26 miles) from the site, as input and allowed WXgen to estimate daily wind speeds for model testing.

Monthly statistics developed for model evaluation

In addition to daily climate data, some models require monthly estimates of means and other statistics for climate parameters as input. This section describes the monthly data developed for model evaluation using measurements from lysimeter Y101d at Coshocton, Ohio as reference.

Monthly precipitation and temperature statistics required include:

- Monthly average, maximum daily temperature
- Monthly average, minimum daily temperature
- Monthly average, mean daily temperature (for HELP)
- Monthly standard deviation of daily maximum temperature
- Monthly standard deviation of daily minimum temperature
- Average total monthly precipitation
- Monthly standard deviation of daily precipitation
- Monthly skew coefficient for daily precipitation
- Monthly probability of wet day after dry day
- Monthly probability of wet day after wet day
- Monthly average, number of days of precipitation

The monthly statistics were calculated from the 37-year (1957 – 1993) record of precipitation and maximum and minimum temperature measurements for the NAEW, Coshocton, Ohio as reported in the National Climatic Data Center records (NCDC, 2001). The statistics were derived by the computer program WXParm (WXparm, 1999) and missing daily data were then estimated by Wxgen (WXgen, 1999). Finally, the revised and complete file was again evaluated with Wxparm to produce a final set of statistics. The results of these calculations are contained in Table I-1.

Table I-1. Monthly data for model estimates at Coshocton, Ohio

Monthly data and statistics assembled for use in all model evaluations using the measurements from lysimeter Y101d.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann	
0.43	2	8.02	14.92	20.79	25.35	27.53	26.82	23.29	16.85	9.87	2.87	14.90	TMX
-8.31	-7.14	-2.02	4.25	10.08	14.63	17.09	16.32	12.71	6.08	0.16	-5.24	4.88	TMN
6.84	6.86	7.4	6.86	5.45	4.02	3.24	3.29	4.71	5.7	6.43	6.67		SDMX
6.8	6.53	5.89	5.42	4.78	3.71	2.93	3.07	4.48	4.84	6.96	6.33		SDMN
55.92	51.6	76.7	84.67	92.59	100.86	112.24	80.96	74.3	57.43	75.54	63.99	926.8	PRCP
6.77	7.35	8.3	9.01	9.46	13.95	13.92	11.62	12.03	8.03	8.51	6.84		SDRF
2.288	2.911	3.593	2.368	2.37	3.122	2.596	1.98	3.456	2.522	2.455	2.143		SKRF
0.289	0.288	0.338	0.316	0.286	0.258	0.277	0.23	0.223	0.226	0.293	0.286		PW|D
0.414	0.401	0.439	0.475	0.483	0.44	0.358	0.36	0.383	0.368	0.43	0.479		PW|W
10.24	9.16	11.65	11.27	11.03	9.46	9.35	8.19	7.97	8.16	10.19	11		DAYP
6.72	9.29	12.67	14.65	20.26	23.53	22.87	20.49	14.59	11.43	7.61	6.38	14.21	RAD
0.9	0.81	0.57	0.61	0.62	0.62	0.66	0.68	0.66	0.68	0.64	0.73	0.68	RHUM
5.21	5.11	5.29	5.07	4.29	3.85	3.42	3.22	3.53	3.94	4.97	5.02	4.41	WIND[1]

1. New Philadelphia, Ohio wind data

TMX = Monthly average, maximum daily temperature, deg. C
TMN = Monthly average, daily temperature, deg. C
SDMX = Monthly standard deviation of daily maximum temperature
SDMN = Monthly standard deviation of daily minimum temperature
PRCP = Average, total monthly precipitation, mm
SDRF = Monthly standard deviation of daily precipitation
SKRF = Monthly skew factor for daily rainfall
PW|D = Monthly probability that a wet day will follow a dry day
PW|W = Monthly probability that a wet day will follow a wet day
DAYP = Monthly average number of days with precipitation
RAD = Monthly average, total solar radiation, Mj/m^2
RHUM = Monthly average, relative humidity, fraction
Wind = Monthly average, daily wind speed, M/s